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# Working Memory, Language, Reading and Behavior: The Importance of Laterality, Symbolism and Default Networks

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## Abstract

The present review draws attention to the importance of working memory, not just for cognitive development, but also for language-related reading skills. The classical work of Patricia Goldman-Rakic drew attention to the advent of language in human development in allowing the efficient use of symbolic 'goals' to be held in working memory throughout the processes of goal achievement (sometimes over long periods of time). The role of a switching mechanism between cognitive, language and default circuits allows the recruitment of salient emotional and/or memory information during the process of goal completion. When these systems malfunction, the often-described comorbidities between conditions such as ADHD, language and learning disability, and behavior problems may be observed. At a developmental level, the capacity for symbolic representation in working memory is likely to be important for early orthographic and later comprehension in reading ability. More recent work has drawn attention to a specific role for selective cerebellar working memory selective areas such as lobules V11b/V111a in supporting parallel cortico-cerebellar visual working memory networks, a new specific role for cerebellar/cortical connections.

**Keywords:** working memory, language, reading, symbolic representation, brain circuits

## 1. Introduction

While the measurement of school readiness in preschool children has largely depended on measures of social readiness in terms of capacity to relate to peers individually and in groups, as well as capacity to follow directions, objective measures of early cognitive development are currently lacking. The present review examines early studies of Working Memory in animals and humans [1] up to current brain mapping cerebra-cortical studies [2].

Blackburne et al. [3] have drawn attention to maturational neurological differences between children and adults in recognition of typical and reversed letters. Lachman and Geyer [4] pointed out that many of the sub-functions involved

in reading are complex processes, in their own right. “For visual object recognition, symmetrically related objects are learned to be represented by similar patterns of neural activity, while such symmetry generalization is a hindrance in reading.”

Levy and Young [5] demonstrated a relationship between letter reversals and attention in ADHD children. It has been shown that children especially boys who are comparatively young compared with grade peers are at risk of being labeled and treated for ADHD [6]. Additionally, such children may be disadvantaged by a maturational deficit in pre-literacy skills which continues to affect their progress in later grades. Ideally an evidence-based test of pre-literacy skills should help parents and preschool teachers in making a difficult decision currently often based on availability and cost.

Thus, according to the above authors, a failure in suppression of visually symmetrical information in the representation of visual symbols produces ambiguous relations between visual and phonological information, which can cause problems in learning to read. Duff and Clark [7] have pointed out that: “Learning to read and spell depends on grasping the principle that particular graphemes (letters) are represented by particular phonemes. Grapheme phoneme correspondence for <t> <a>, and <p> according to the authors allows application to decode ‘tap’, ‘apt’ and ‘pat’.

However direct and longitudinal measurement of the relationship between orthographic and phonemic developmental skills in preschool children has not been reported. The present review draws attention to the importance of working memory, not just for cognitive development, but also for language-related reading skills. The classical work of Patricia Goldman-Rakic [1] drew attention to the advent of language in human development in allowing the efficient use of symbolic ‘goals’ to be held in working memory throughout the processes of goal achievement (sometimes over long periods of time). The role of a switching mechanism between cognitive, language and default circuits allow the recruitment of salient emotional and/or memory information during the process of goal completion. When these systems malfunction, the often-described comorbidities between conditions such as ADHD, language and learning disability, and behavior problems may be observed. At a developmental level the capacity for symbolic representation in working memory is likely to be important for early orthographic and later comprehension in reading ability.

## **2. ADHD and reading comorbidity**

While comorbidity between ADHD and learning disabilities has been reported clinically for many years, few studies have investigated the frequency, and even fewer have postulated an underlying pathophysiology of this important association [8]. The authors reported that a total of 17 studies between 2001 and 2011 that examined ADHD-LD (Attention Deficit Hyperactivity-Learning Disability) comorbidity suggested a higher mean comorbidity rate (45.1%) than had been previously obtained, when reading, writing and mathematics disorders were included. The present review investigates the key role of language and reading abilities in human working memory and relation to ADHD and learning disability. The development of linguistic representation has allowed increased capacity for task achievement and planning, as well as working memory integration of verbal and visual symbolism important for reading and spelling. Cognitive mechanisms that facilitate appropriate switching between executive and default networks is also discussed in relation to possible comorbid ADHD-LD deficits.

Tierney and Nelson [9] have discussed brain development and the role of experience in the early years. The authors described the importance early synaptogenesis

and subsequent synaptic pruning [10] in the laying down of language and facial processing systems as the basis for later cognitive and emotional functions. An important modulator of early behavior is the capacity for maintenance of a goal in working memory. While primates are characterized by advanced development of binocular vision resulting in stereoscopic depth perception, specialization of the hands and feet for grasping, and enlargement of the cerebral hemispheres, humans are importantly capable of symbolic working memory goals.

### 3. Representation of discriminative stimuli

Goldman-Rakic [1, 11, 12] described the importance of activity in the prefrontal cortex during working memory tasks and the ability to guide behavior by representations of discriminative stimuli rather than by the discriminative stimuli themselves as a “major achievement of evolution.” According to Goldman-Rakic [1], this capacity was shown to depend on the bilateral integrity of the dorsolateral prefrontal cortex [13, 14]. The capacity was believed to have mnemonic, temporal-sequential, spatial perception/orientation and attentional and motor control functions that allowed correct responses and disallowed or inhibited incorrect responses. Goldman-Rakic [11] drew attention to the distinction between working and associative memory, and the pre-eminent role of the prefrontal cortex in the former. She found that the dorsolateral prefrontal cortex (PFC) contained a local circuit that encompassed short-term memory, attentional and response control mechanisms in the principal sulcus of the dorsolateral PFC (DLPFC) and postulated a superior to inferior localization of spatial, object and linguistic processing with a common architecture for their network organization. She also described parallel connections with the posterior parietal cortex and feature working memory areas of the inferior prefrontal cortex and area TE in the temporal lobe. Posterior parietal regions were believed to carry **directionally specific** information in all phases of the delayed response task from cue to delay and response and to mirror those in the prefrontal cortex. She proposed that the central executive should be considered as an “emergent property of co-activation of multiple parallel domain-specific processors located in the PFC and interconnected with domain-relevant long-term storage sites in the posterior sensory regions of the cortex and appropriate motor pathways” [11]. Levy and Farrow [15] discussed the role of prefrontal/parietal connections in sustaining activation during an A-X continuous performance task and facilitation by administration of methylphenidate. The classical work of Goldman-Rakic in drawing attention to the central role of **representational** cuing ability in working memory is central to the present argument.

### 4. Current brain mapping

If we fast-forward to current brain-mapping approaches to large-scale brain systems, Castellanos and Proal [16] have postulated a number of “resting state” and candidate neural and attentional systems, thought to be of importance in ADHD psychopathology. Interestingly they describe a “dorsal attentional network, which mediated goal-directed, top-down executive control processes, particularly in re-orienting attention during visual attentional functioning, with key nodes in the intraparietal sulcus (BA40) and the frontal eye fields ((BA6), the latter being perhaps the converse mirror image of the DLPFC above”.

The work of Sonuga-Barke and Castellanos [17] drew attention to the “anti-correlation” of executive vs. default networks for ADHD, suggesting that ADHD



was characterized by inappropriate default intrusions during working memory. Mechanisms that control the rapid and transient switches from executive to default mode are not well understood. Menon and Uddin [18] have postulated that the anterior insula and the anterior cingulate cortex form a “salience network,” “that functions to segregate the most relevant among internal and extra-personal stimuli in order to guide behavior.” The authors described two critical networks whose activation and deactivation is observed during cognitive tasks: the central executive network and the default network. The former was thought to include the dorsolateral prefrontal cortex (DLPFC), posterior parietal cortex (PPC), while the default mode network included the ventromedial prefrontal cortex (VMPFC) and posterior cingulate cortex. While the central executive was important for the active maintenance and manipulation of working memory during goal-directed behavior, the default network including medial temporal lobe and angular gyrus, in addition to PCC and VMPFC, were active during tasks that involved autobiographical memory and self-reference. Furthermore, a third coupling of the anterior insula (AI) and anterior cingulate cortex (ACC) was thought to be “involved in transient detection of salient stimuli and initiating attentional control signals, which are then sustained by the ACC and the ventrolateral and dorsolateral PFC.”

The AI was believed by Menon and Uddin [18] to have a critical role in switching between large-scale networks to facilitate the saliency of attention and working memory resources. Importantly, the AI and ACC have been found to contain von Economo neurons (VEN's) with large axons that facilitated rapid relay of AI and ACC signals to other cortical regions, and function as a switch mechanism between central executive and default mode. The authors postulate that AI pathology could account for deficits in social processing in conditions such as autism when hypoactive, as well as auditory verbal hallucinations when hyperactive, and attentional deficits in a number of pathological conditions.

Allman et al. [19] described the presence of VEN's in humans and apes only. The authors utilized diffusion tensor imaging in a gorilla brain to show connection of VEN-containing regions to frontal and insular cortex, septum and amygdala. They postulated that VEN's activity could be evolutionarily derived from gut/appetite monitoring at neuronal level, allowing rapid reactions to changing conditions. (Wikipedia suggests that significant olfactory and gustatory capabilities of the ACC and fronto-insular cortex have been usurped during recent evolution to serve enhanced roles in higher cognition). Fajardo et al. [20] also described a group of cells with similar morphology to VENS in the dorsolateral prefrontal cortex of humans (described by Goldman-Rakic [1] as important for working memory functions).

## **5. Default language network, reading and development**

The importance of working memory for reading comprehension was studied by Gonzalez-Perez et al. [21] who investigated electrophysiological correlates in 52 Spanish ADHD children divided into those with and without reading comprehension deficits. The authors pointed out that “working memory is essential for reading sentences because noun and verb phrases tend to be situated apart from each other, and they need to be maintained and attached in the proper order to be comprehended.” For anaphoretic phrases (the use of a word, referring back to a word used earlier in a text or conversation, to avoid repetition, e.g., pronouns), the gender of a subject and its pronouns are the only clues to achieve agreement. Where there is gender or number disagreement, electrophysiological evoked potential (ERP) recordings of components such as early left anterior

negativity (ELAN) and left anterior negativity (LAN) and P 600 are affected. ELA is described as emerging 200 ms after stimulus presentation, whereas LAN is seen at from 350 to 550 ms, and believed to represent the first syntactic parsing of sentences using lexical information. On the other hand, P600 is a later component, seen between 500 and 900 ms, also reflecting agreement violations and possible attempts to repair incorrect alignments. Gonzalez-Perez et al. [21] utilized ERP measurements in ADHD children with and without reading comprehension deficits and normal controls. They demonstrated that ADHD children without reading comprehension deficits and control children began morphosyntactic agreement processing in the first 100 ms after the appearance of a target, while the ADHD children with reading comprehension difficulty appeared to begin this processing 250 ms after appearance of the target, suggesting impairment of working memory processes in reading comprehension in those children.

## 6. Linguistic approaches to working memory

In relation to symbolic aspects of working memory, it is useful to compare Spanish, French and English linguistic (anaphoretic) experiments; in that, Spanish and French languages utilize gender-based pronouns for both people and objects, while in similar English experiments, gender is specifically related to people. Carreiras et al. [22] investigated 'surface' pronouns in three Spanish language experiments in which non-semantic gender pronouns matched their antecedents on the basis of 'morphosyntactic' properties alone. That interpretation of pronouns referring to things was speeded by a syntactic gender match. Garnham et al. [23] reported three similar experiments in Spanish and French in which the interpretation and response times of pronouns for morphological vs. semantic (superficial vs. deep) anaphors. By including results from sentences about people and sentences about things, the investigators demonstrated that reading times for subordinate clauses were read more quickly when there was a gender cue. This effect was equally large for people and things, but stronger for people references when subsequently questioned. In a third French experiment the authors found that while the gender cue in pronouns about things was strong, this 'superficial' representation became less readily available over time, when grammatical or semantic references became more important.

Friedman et al. [24] have investigated ADHD and working memory's contribution to reading comprehension and applied maths problem-solving abilities. The authors describe working memory (WM) as a "limited capacity, multi-component system responsible for temporarily storing and processing sensory information." They suggest that the working component of WM or Central Executive (CE) is "responsible for focusing attention, inhibiting irrelevant information from accessing focused attention, and updating, manipulating and reordering information stored within two anatomically distinct subsidiary memory systems-the phonological (PH) and visuospatial (VS) short-term memory subsystems-which are responsible for the temporary storage and maintenance of verbal and non-verbal visual/spatial information, respectively." According to the above authors, few studies have examined the hypothesis that WM plays key roles in reading comprehension (and applied mathematics). These studies have found that phonological WM (using CE and PS STM and/or visuospatial VS STM) jointly contributed to reading comprehension. However, they found that no study had dissociated the three important WM components (CE, PHSTM and VSSTM) to determine their unique contributions to the difficulties of children with ADHD.

Friedman et al. [24] compared two groups of children aged 8–12 years, namely a group with ADHD Combined Inattention/Hyperactivity and a typically developing group. They utilized computerized - phonological and visuospatial working memory tasks. According to the authors, these tasks measure the ability to mentally store, rehearse and manipulate the serial order of verbal or spatial stimuli. Additionally, reading comprehension (KTEA Reading Comprehension standardized four potential mediating variables: subtest scores as well as Orthographic Conversion scores were analyzed. The latter factor score reflected an estimate of overall orthographic conversion ability via an Orthographic Conversion Speed Task and a KTEA Reading Recoding/Letter-Word task [24]. The investigators analyzed four potential mediating variables, PHSTM, VSSTM, CE and Orthographic conversion to determine whether they independently contributed to ADHD-related Reading Comprehension difficulties. Only CE and Orthographic Conversion were found to emerge as significant partial indicators of the relation between Diagnostic Status and Reading Comprehension. Subsequent modeling indicated that the collective influence of CE and Orthographic Conversion fully accounted for between-group differences in reading comprehension and explained 61% of the variance between diagnostic status and reading comprehension. The authors commented that the failure of some computer-based WM interventions could be explained by misspecification of intervention targets. The study highlights the association of central executive working memory and visuospatial orthographic processes affecting reading in ADHD children. The latter effect may indicate a representational cuing effect, as originally described by Goldman-Rakic [1].

## **7. Maturation effects**

Friederici, Brauer and Lohman [25] have described a maturational functional re-organization of the neural network, underlying language development, believed to allow a close interplay between frontal and temporal regions within the left hemisphere. The investigators utilized correlational methods, based on the analysis of low frequency fluctuations, previously used in resting state studies. They were able to identify a network with a strong correlation between the ventral part of the inferior frontal gyrus (IFG) and superior temporal sulcus (STS)/superior temporal gyrus (STG/STS).

The above authors investigated age-related comparisons of six-year old children and adults that demonstrated important differences between the child and adult subjects, using an auditory sentence comprehension paradigm. They analyzed functional connectivity between the left inferior frontal cortex and the posterior superior temporal gyrus (STG/STS). Their statistical analyses concentrated on perisylvian areas in the inferior frontal and superior temporal cortices in both hemispheres. “When seeded in the left, Brocas Area 44 (BA44), strong correlations were obtained with the left posterior temporal cortex in adults, whereas in children no such ipsilateral correlation was observed,” but “children showed stronger correlations of BA44 with the contralateral inferior frontal region.” The authors suggested that a general lateralization principle underlying the normal development of cognitive processes applied to the development of the default network for language.

Tomasi and Volkow [26] investigated the maturation, during childhood and adolescence, of functional connectivity of the substantia nigra vs. ventral tegmental areas in 402 healthy children/adolescents and 704 healthy young adults, as well as 203 children with ADHD. The investigators pointed out that VTA midbrain neurons give rise to the mesocorticolimbic pathway, while the substantia nigra midbrain DA neurons give rise to the nigrostriatal pathway. The investigators mapped functional



connectivity orthogonal resting state patterns, utilizing brief magnetic resonance imaging (MRI). They demonstrated reproducible VTA and SN connectivity patterns. Interestingly, typically developing children (TDC) showed preferential VTA connection with subthalamic nucleus, globus pallidus, thalamus and vermis, while for adults VTA was additionally connected with the mesolimbic pathway (nucleus accumbens, hippocampus and para-hippocampus) and with the anterior insula. Thus, according to the authors, limbic regions showed strong connection with VTA in adults, but an unexpected strong connection with SN in typically developing children. There were also strong lateralization effects in Broca's (cortical area involved with speech production and Wernicke's cortical area involved in speech reception) that were more pronounced in adults. The investigators interpreted their results as showing age-related increases in functional connectivity of the VTA with limbic regions and the default mode network, and by decreases in connectivity of the SN with motor and medial temporal cortices, indicating a change from SN influences in childhood/young adolescence and a combined SN and VTA influence in young adulthood. Furthermore ROI (region of interest) analysis showed that ADHD children had stronger SN connectivity in left amygdala and insula than normally developing children, and stronger VTA connectivity in thalamus, subthalamic nucleus and globus pallidus than TDC. This pattern was thought to be consistent with delayed maturational pruning of the connectivity patterns in these regions.

## 8. Discussion

A number of differing research approaches and the advent of sophisticated brain mapping techniques have drawn attention to the importance of default mode access and regulation in both normal and pathological working memory regulation processes. Executive function is thought to depend on cortico-striatal-thalamic-cortical integrity [27], while the default mode is postulated as an associative, internally directed and 'anti-correlated' network, with overlapping hubs related to semantics, salience and language [28]. It is now believed that far from a passive resting cognition, default cognitions have important integrative roles in both utilizing past salient memories and establishing future orientations. Importantly, the control of ongoing switching activity between executive and default circuits may be central in determining when and whether default activities, such as day-dreaming and fantasy are productive or pathological. In the present context, the linguistic use of pronoun gender anaphors are an example of representational cues used to maintain comprehension of separated noun/verb clauses. In this respect, von Economo cells in the anterior insula have appeared to be one central area in switching rapidly from default, language and salience circuits to executive functions. Executive functions are feedback controlled and relate back to representations in the prefrontal cortex, while the default mode associations are thought to help integrate emotionally based experiences and recollections of episodic memory. Optimal cognitive function requires smooth transition between executive (external) and internal (default) cognitions. When these switching mechanisms are impaired, pathological conditions such as ADHD, autism and behavior disorder may develop.

The present review draws attention to the importance of working memory, not just for cognitive development, but also for language-related reading skills. In this regard, the advent of language in human development has allowed the efficient use of symbolic 'goals' to be held in working memory throughout the processes of goal achievement (sometimes over long periods of time). In addition, the description of a switching mechanism between cognitive, language and default circuits facilitate



the recruitment of salient emotional and/or memory information during the process of goal completion. When these systems malfunction, the often-described comorbidities between conditions such as ADHD, language and learning disability, behavior problems (and autistic syndromes) may be observed. At a developmental level the capacity for symbolic representation in working memory is likely to be important both for early orthographic and later comprehension in reading ability.

The interaction of language, early reading and attentional skills has important implications for future studies of kindergarten readiness and gender differences in preschool children. Additionally, a recent review of cerebellar effects on fast-acting internal brain models, has described both forward and reverse effects on both tool use and cognitive functions [29]. Forward models are able to update internal circuits with rapid effects on cortical and subcortical structures, allowing adaptation of motor performance errors. However, addition, there are hypotheses that the cerebellum is involved in modification of language processing, particularly in correction of well-established semantic processes. The addition of rapid cerebellar corrections with maturity, adds an error correction component to cortical, subcortical and cerebellar circuits involved in language development.

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