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REVIEW ARTICLE

Working Memory and Executive Attention: Insights from Developmental Studies and Implications for Learning and Education

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Abstract | Working memory and executive attention enhance the processing of relevant information for goal-directed behavior. Working memory is generally defined as the ability to hold and manipulate information for the current processing and may facilitate learning, planning, reasoning, and problem solving. Executive attention involves monitoring and resolving conflict among thoughts, feelings, and responses. Maintenance, manipulation, and updating components of working memory interact with executive attention and influence many higher order cognitive processes such as decision-making, cognitive control, language processing, and social cognitive processes. Development of working memory across the life span particularly from early to late childhood has been explained in terms of resource allocation, target representations, inhibition, and processing of distractors. Development of the two non-unitary processes correlates with learning and education. In this review, we discuss the development of working memory, executive attention, and developmental studies on the interaction between the two processes and how this is critical for learning and education.

Keywords: *Development, Working memory, Executive attention, Education, Working memory models*

1 Introduction

Working memory and executive attention are the two processes, which help in holding the memory items in the workspace and enhance the processing of relevant items for goal-directed behavior. Working memory (WM) is generally defined as the ability to hold and manipulate information for current processing.[1] By definition, it has two components: one is storage and the other is the processing component. Working memory is more than just holding information in one's mind. It involves performing many mental operations; for instance, rearranging the items which we are holding our mind or examining the relationship between them.[2] Executive attention (EA) or executive control involves monitoring and resolving conflict among thoughts, feelings, and responses.[3] Understanding the developmental trajectory of working memory and executive attention will help to investigate how these processes emerge and interact with each other during the rapid ongoing development of brain and higher order cognitive processes. In this review, we first discuss the various models of working memory, which also emphasize the role of attentional mechanisms and how the current literature particularly looks at the interaction between working memory and executive attention. We have particularly discussed the developmental studies on the interaction between working memory and executive attention substantiated with a sample behavioral study. We end with a brief discussion about the implications of this interface for learning and education.

Working Memory: The ability to hold and manipulate information for current processing

Executive Attention: Executive attention involves monitoring and resolving conflict among thoughts, feelings, and responses.

Learning: Learning involves acquiring new information or modifying and reinforcing the existing knowledge, behaviors, and skills.

Education: Education is the process of facilitating learning and acquisition of knowledge.

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Episodic buffer: The episodic buffer component of working memory involves integrating the information from long-term memory and storage system.

Phonological loop: The phonological loop is a component of working memory, which stores verbal representations.

Visuo-spatial sketchpad: The visuo-spatial sketchpad is a component of working memory, which stores both visual and spatial information.

Central executive (CE): The CE component of working memory responsible for regulating the information and acting on it to achieve the goal.

Maintenance: Maintenance in working memory involves storage of information for short period of time.

Functional magnetic resonance imaging (fMRI): Functional MRI is a non-invasive neuroimaging method, which measures brain activity in terms of changes in blood flow.

Multi-voxel pattern analysis (MVPA): The MVPA is a multivariate method to classify or predict neuroimaging scans. Data from individual voxels within a region are jointly analyzed in this multivariate approach.

Manipulation: Manipulation in working memory involves online processing of stored information.

1.1 Models of Working Memory

There are various models of working memory,[4] first and foremost is the multi-component model proposed by Baddeley and Hitch[5] which highlights the structural organization of the working memory components including two slave storage systems, one executive system, and one episodic buffer. The two storage systems store two different kinds of memory representations. Phonological loop stores verbal representations and visuo-spatial sketchpad stores both visual and spatial information, whereas central executive is mainly for regulating the information and acting on it to achieve the goal, and finally, episodic buffer allows integrating the information from long-term memory and storage system to provide a comprehensive view of working memory. Initially, neurophysiological and neuroimaging studies showed that there is persistent neural activation in prefrontal cortex during the delay period of the delayed response task.[6,7] However, when the storage is pitted against the similar stimulus like faces and houses different neural areas are recruited and this is true for the different kinds of stimuli.[8,9] To account for the evidence of recruitment of different type of neural architecture for slightly different stimuli, multi-component model theoretically should compartmentalize huge number of stimulus into different storage buffers and similar compartmentalization is demanded in the prefrontal cortex.[10] Postle[10] proposed that working memory is an emergent property of the nervous system with the capabilities representing different types of information and the attentional allocation to the perceptual or long-term representations brings them into the heightened accessible state called working memory. Similarly, recent developments in the analysis of functional magnetic resonance imaging (fMRI) data like multi-voxel pattern analysis (MVPA) show that low-level stimulus like color, orientation, and motion are maintained in the visual areas which also encode those same stimuli.[11, 12].

The other two prominent models in working memory literature are the Cowan's "Embedded processing model"[4] and the "Dual Component Model".[13] The two models consider working memory as part of long-term memory (LTM). Cowan's model[14] argues that the activated zone of the LTM is WM. Engle and Kane[13] consider that WM has two components one is storage and other is executive control. The individual differences in working memory capacity come due to the ability to deploy executive control processes in working memory tasks. Cognitive models proposed by Cowan and colleagues,[14] Oberauer and colleagues,[15] and McElree[16] argue that working memory is a state of activation rather than a separate component and the activation is achieved through the attention to internal representations of long-term memory. Cowan and colleagues[14] proposed two activation states, one is activation of WM within long-term memory and another is focus of attention (FOA). Oberauer and colleagues[15] have proposed a three-state model including activated long-term memory, direct access state and FOA, maintaining single item at a time. Nature of capacity limitations in working memory determines how many items and with what precision those items can be maintained at a time in FOA.

Two contrasting models are proposed to explain the nature of representations in working memory, i e., Slot models and resource models. Slot models posit that working memory representations are discrete in nature and follow all or none principle, i e., either an item is stored with high precision or is not stored at all in the slots with the highest storage of 4 items at a time.[17, 18] Cowan's model[14] described above is a slot model. Resource model posits that working memory is constrained by the availability of resource, which is shared between the items to actively maintain the items in memory. Resource allocation to the items has also been proposed to be dynamic in nature and can be varied from trial to trial.[19] Resource models allow for more dynamic adjustments in the maintenance of items.[20].

The time-based resource sharing (TBRS) model[21] is one of the resource models and is based upon two opposing processes: 'Temporal Decay' and 'Attentional refreshing of Memory Traces' and also explains the interplay between these two processes. This model proposes that the items on which attention is focused receive activation, and thus, memory traces are formed. The memory traces decay during processing of distracters and are refreshed during brief pauses amidst processing. Representations in WM are known to decay over time and can be refreshed by directing attention over them. Within complex tasks, processing as well as maintenance of information relies on the same resource; attention. According to this model, attention must be shared between processing (manipulation) and storage (maintenance). Thus, in a way, this model also talks about maintenance and manipulation being governed by different set of processes. As in a dual task, as soon as attention is switched away from a memory item, its activation suffers from time-related decay. During this time, the task being processed occupies attention and memory traces cannot be refreshed during this time. High working memory load leads to greater distractor effects, as compared to a low working memory load. The effect of working memory load also depends on the task, whether it involves maintenance or manipulation. Both these processes involve attentional mechanisms in terms of filtering the relevant while suppressing the irrelevant information. The existing models of working memory have highlighted the capacity limitations in terms of storage or maintenance in WM and resource sharing by recruiting attentional mechanisms to refresh items in WM as well as for manipulation of information in WM. Demands on attentional mechanisms for maintenance and manipulation in working memory are particularly high in the case of competing information and conflict resolution.

1.2 Executive Attention

Executive attention involves attention mechanisms implicated in the control of thought, affect, and behavior. Although the term executive attention overlaps with a broader construct called executive functions (cognitive flexibility, inhibitory control and working memory), executive attention particularly involves resolution of conflict between the competing stimuli or inhibiting the prepotent response and selecting the non-dominant response.[22] Executive attention is often measured through conflict tasks like Flanker,[23] Stroop and Simon tasks[24] which measure conflict resolution by looking at the differences in reaction times between the incongruent and congruent trials. Conflict monitoring model states that when the conflict is detected between the target and distractors, top–down modulation of attentional control biases the competition to further process the target signal or inhibit the distractor processing. When the conflict is detected dorsal anterior cingulate cortex generates a signal and the dorsolateral prefrontal cortex regulates the conflict through top–down modulation and resolves the conflict.[25] Unlike conflict monitoring model, dual network model proposes two independent top–down regulation networks involved in resolution of conflict. Fronto-parietal network shows transient activity during the instruction phase of the task and might be involved in task adjustments during the task. Cingulo-opercular network shows sustained activity throughout the task and is assumed to maintain the parameters or task sets required for the task at hand. Thus, executive attention is likely to participate in the maintenance and manipulation of information in working memory.

1.3 Interaction between working memory and executive attention

Working memory coordinates processing to guide behavior when many goals are active. Information is registered in working memory by allocating attention to information. Researchers have highlighted the overlapping mechanisms of working memory and attention referring to various aspects of both the processes.[26] The top–down modulation may influence early perceptual representations and may modulate neuronal excitability during encoding as well as maintenance in working memory.[27] Neuroscientists believe that the top–down control signals from the prefrontal cortex (PFC) either enhance task-relevant information or suppress irrelevant information.[28] Studies using repetitive transcranial magnetic stimulation (rTMS) have shown PFC mediated top–down modulation in the early perceptual stages on working memory encoding and subsequent storage of task-relevant information.[29] In addition to early perceptual processing while encoding, successful performance on working memory tasks with increasing load involves executive control and inhibition. Hu and colleagues[30] investigated the role of executive control in visual working memory using an object working memory task and found that maintenance or storage in working memory reflects the involvement of top down and stimulus driven executive control. Cognitive neuroscience literature on working memory and executive control highlights the hierarchical as well as top–down, since PFC represents higher order information including task goals, rules, or abstract representations[31] compared to sensory stimulus specific representations in the posterior cortex. Most of the studies using fMRI, electroencephalography (EEG) and other methodologies provide evidence for state-based models of WM, suggesting that selective attention mechanisms bring the mental representations into WM.[28]

Diamond[32] in her review argues that working memory and executive attention (withholding pre potent response to make non- dominant response or interference suppression) work hand in hand. Working memory is used for storing the mental representations, which are goal-specific and inhibitory control for reducing the distractor interference, so that goal-specific representations

Inhibitory control: Inhibitory control involves the ability to voluntarily inhibit a prepotent/ongoing response. It also involves the ability to attend to the relevant information while inhibiting the irrelevant information.

Simon Task: The Simon task is a choice reaction time task in which there is a dimensional overlap between the irrelevant stimulus and the response. This task measures response selection-based conflict by looking at the consistent versus inconsistent trials based on the stimulus response mapping.

Prefrontal cortex (PFC): The PFC is that part of the brain, which covers the front region of the frontal cortex. PFC is involved in higher order executive functions including executive control and working memory.

Conflict monitoring: Conflict monitoring is a form of cognitive control, which involves monitoring of conflicts in information processing.

Transcranial magnetic stimulation (TMS): The TMS is a non-invasive technique and works by stimulating a region of the cortex placed beneath a current carrying coil. TMS works on the principle of electro-magnetic induction. The stimulation temporarily interferes with ongoing cognitive process in that particular region and thus informs about the necessity of that region for the process in question.

Neuroscience: Neuroscience is a scientific study of the structure and function of the nervous system.

Electroencephalography (EEG): EEG is an electrophysiological method, which provides a graphical representation of the difference in voltage between two different cerebral locations plotted over time.

enter into working memory. According to load theory, selective attention system has two processes, one is the passive perceptual process and other is the active control process.[33] As the perceptual load increases the processing of distractors decreases, whereas increase in working memory load increases the processing of distractors. In general, this pattern of results is shown using dual task paradigms where selective attention is introduced during the retention period of the delayed response working memory task and comparing the processing of distractors in high and low perceptual and working memory load. Using the working memory task and the ability to process distractors in the flanker task (executive attention task), the results, indeed, showed that high working memory load increases the processing of distractors compared to the low working memory load.[33] The opposite effect was seen in perceptual load condition, and Lavie and colleagues[33] were able to dissociate these processes in the same experiment. They also demonstrated the cost of task switching effects when the two tasks are performed resulting in an increase in the overall reaction times. However, the evidence from these experimental findings have been criticized[34, 35] arguing that the domain general effect of WM load on selective attention task was absent during high working memory load only when the contents in the selective attention task matched the content of information to be maintained in the WM task. Otherwise, when the contents in the WM task matched with that of the distractors in the selective attention task, performance on the attention task improved. These two studies showed that the effect of working memory load on the selective attention task is content-specific.

Flanker task: The flanker is used to measure conflict resolution consisting of congruent and incongruent stimuli.

Fockert[36] in his review on working memory and selective attention argues that the nature of the effect of working memory load on the selective attention task is domain general. His review addresses two important questions: (a) what components of working memory share the mechanisms in attention? (b) what mechanisms in selective attention explain distractibility as a function of availability of working memory? For the former question, he proposes that it could be the central executive in working memory, but it does not really explain the nature of tasks used in earlier research, because it is the processing component of working memory and the task used may tap the maintenance aspect of WM rather than manipulation. However, he argues that it could be the indirect effect of working memory, which shares the limited resource mechanism for distractor rejection with selective attention. For the latter question, he provides two possible mechanisms, one including the temporal aspect of selective attention and other related to the spatial aspects of attention. Increase in working memory load constrains the selection of target representations temporally or could affect the distribution of spatial attention.

The interaction between working memory and attention could also be investigated and better understood in the context of rapid ongoing development of these higher cognitive processes correlated with the protracted development of neural mechanisms that underlie these processes. An understanding of this interface with a developmental perspective has far reaching implications with respect to cognitive development, learning, and education in addition to providing insight into the shared mechanisms of the two cognitive processes.

2 Development of working memory and executive attention

2.1 Development of Working Memory

Working memory affects many aspects of learning. Children who have difficulties with attention and learning may also have difficulties with working memory. Development of working memory is known to be progressive and protracted which is also true for other higher cognitive processes including control processes (selection, inhibition, and switching) and their neural substrates.[37–39] In a recent longitudinal study using functional magnetic resonance imaging with children and young adults spanning up to 9 years (12–20 years of age), Simmonds and colleagues[40] have shown protracted development of WM into the early 20s. Their fMRI-based region of interest analysis showed increase in activations in the visual cortex and decrease in activations in the executive regions from childhood to adolescence. However, findings vary with respect to maintenance vs manipulation components of WM. For instance, developmental improvements in manipulation relative to maintenance in WM (using an object WM task) have been associated with greater involvement of dorsolateral prefrontal cortex and superior parietal cortex[41] and thus show age-related differences until adolescence.

To track the development of working memory from the Baddeley's multi-component account, Gathercole and colleagues[42] conducted a study in the age group of 4–15 years. In total, nine tests were administered on children, three tests measuring each component of working memory, which includes phonological loop, visuo-spatial sketchpad, and central executive. The results indicated no correlation between visuo-spatial sketchpad and phonological loop tests at age 6, which is indicative of structural differentiation of storage systems at this age, though they found improvement in performance on each component as the age increased. However, there was no change in the strength of the relationship between the three components developmentally. Alloway and colleagues[43] showed that the structural differentiation between the three components occurs by 4 years of age. The most important finding of this study is that the strength of the relationship between the three sub-components remained the same as the age increased except for the verbal storage system. Although these two studies inform about the age at which structural differentiation between the components of working memory occurs, yet they do not inform about the interaction between the storage and processing components of working memory.

Luck and Vogel[17] studied object working memory maintenance in young adults using a variation of the delayed response task (change detection task). In this task, the participant has to store the number of objects in the array, and after a brief delay period, they have to respond if there is any change in the array or not. They found that the performance of the participants was good when it required storing 3–4 units, but the performance reduced with an increase in the array. The calculated capacity for storage showed that an individual could store 4 units at one point in time. This method acts a way to measure storage capacity of object working memory. The visual working memory capacity (VWMC) in children from the age group of 8–11 years was studied[14] using a variation of Luck and Vogel[17] experiment. Results showed an increase in capacity by 2 items at age 8–4 items at age 11. Riggs and colleagues[44] investigated the VWMC in age groups 5–10 years by increasing the display time of the array to 500 ms and found that VWMC improved with age. Results of both the studies indicate that VWMC reaches adult level of performance by the age of 11 years. Similar findings have been reported with Indian population showing slow progressive growth of visuo-spatial working memory with increasing working memory load in children aged 5–15 years[38, 45]. The proponents of time-based resource sharing model also showed improvements in WM in terms of reactivation process to prevent the memory from temporal decay using focus of attentional control and switching mechanisms after 7 years of age until adolescence.[46] Given that working memory capacity increases with increase in age, it is important to understand how the storage component of working memory interacts with the processing component which involves cognitive control provided that working memory maintenance in itself can use different mechanisms like phonological rehearsal, long-term knowledge apart from cognitive control mechanisms.

2.2 Development of Executive Attention

The study of development of executive attention during infancy, early, and late childhood has been an influential area of research due to its implication in a wide range of high-order cognitive functions and developmental outcomes.[47] Reuda and colleagues[22] measured executive attention in the age group of 6–9 years and showed an improvement in conflict resolution until age 7. In the same study, Rueda and colleagues compared the performance between 10 year olds and adults on two variations of the flanker task, one with an array of fish and other with arrows as stimuli. Results showed that the conflict scores for adults were twice as higher on the arrow flanker task compared to fish flanker task, but the difference between the 10 years old and adults was not found on both types of tasks. The conflict scores for 8 years old was 71 ms and for 10 years old was 69 ms. The reason why the fish flanker task showed less difficulty is that the developmental improvements in the flanker task were observed due to increasing efficiency in translating stimulus input into response code.[48] Similar findings were reported in another study where the conflict scores were almost static after 8 years of age.[49] Similarly, in the Indian context, rapid improvement on attention network task (combination of flanker task and cueing task) was observed across 6–11 years of age.[50] However, other studies have found improvement in performance on flanker task as the age increases till 14–15 years. Huizinga and colleagues[51] showed that there is an improvement in the flanker task until age 15. In this study, conflict effect was 135 ms for 7 years old, 64 ms for 10 years old, and 51 ms for 15 years old. Similar results were found in the study conducted by Waszak and colleagues.[52] In the study conducted by Abundis-Gutiérrez and colleagues[53], behavioral results showed that adults showed difference in conflict scores between the age groups of 4–6, 7–9, and marginally for 10–13 years old. The reason for showing the different trajectories of development observed in the flanker task might

Visual working memory capacity (VWMC): The VWMC refers to the amount of visuo-spatial information that can be actively maintained in working memory.

Attention network task (ANT): The ANT was designed to measure the three attentional networks in children and adults namely alerting, orienting, and executive control networks.

be because of several reasons, and one reason could be that the studies showing adult like RT differences shown in flanker task by age 8 used the ANT task and they have not included the invalid trials for measuring orienting network. It has been reported that there is an interaction between the orienting and executive attention network when invalid trials are included.[53, 54] Hence, it is apparent that developmental trajectories of working memory and executive attention are progressive and protracted, and give a way to look at the shared mechanisms between the two processes. This understanding is critical, since the two processes influence many other cognitive processes and skills such as cognitive control, problem solving, reasoning, language processing, reading, and arithmetic.

2.3 Developmental Studies on the Interaction Between Working Memory and Executive Attention

Working memory and executive attention are associated with the anterior attention system, which shows protracted development from infancy to late childhood.[55] Given the emphasis on attentional control and PFC for working memory, development of anterior attention system is critical for working memory.[56, 57] Gains in working memory performance overlap with developmental transitions in the development of alerting, orienting, and anterior/executive attention systems. In addition to the similarity in the neurocognitive developmental trajectory (protracted development) of WM and executive attention, literature on cognitive development has also looked at the development of inhibitory control, processing of distractors, perceptual load or even domain general target representations, and their influence on working memory maintenance and manipulation.

Stroop task: The Stroop task is a measure of interference control. Reaction times are slower for incongruent trials when the target and the distractor feature do not match compared to congruent trials when they do match.

Developmentally, load theory showed that children who have low information processing abilities are able to process less number of distractors because of the passive mechanisms of perceptual processing acting as a counterintuitive mechanism. Load theory predicts that children have less ability to control their attention occurring at late selection compared to adult populations. Huang-Pollock and colleagues[58] varied perceptual load in the letter flanker task for 4th grade (9–10 years old) participants similar to Lavie and colleagues[33] and found that when the perceptual load is increased, the flanker interference also increased for set size 4 and later decreased in young children. This trend in performance was observed at a larger set size (6) for adults. In the same research paper, their second study showed decrease in interference during the smaller set sizes across four age groups. Parallel to the WM and executive attention research, developmental studies on executive functions have also looked at the different mechanisms underlying executive attention. Miyake and colleagues[59] found that there are three core executive functions, which help in goal-directed behavior, including updating, inhibitory control, and task switching. Few researchers claim that WM is in itself enough for goal-directed behavior[60], whereas other researchers claim that it is necessary to understand the relationship between the different executive functions where inhibitory control and working memory are separate and required for goal-directed behavior in children.[32, 61–63]

Three studies[62–64] are of particular importance in studying the interaction between the WM and executive attention developmentally. Davidson and colleagues[62] have studied working memory and inhibitory control through variations in the Simon task (used to measure spatial incompatibility effects) in the age group of 6–13 years. When the WM demand was added to the Simon task, the spatial incompatibility effects disappeared and there was no improvement with age in this task. However, the performance of children was significantly better across age groups when memory demands were absent. Roncadin and colleagues[64] have used a similar paradigm as Davidson and colleagues[62] and found that efficiency measure (including RTs and accuracy) increased in the Working Memory + Inhibitory Control (WM + IC) task (Dots task which is a combination of Simon task and Stroop task) throughout the development compared to the individual task which only requires inhibition or WM. The interactions obtained through the correlational analysis showed that WM + IC task efficiency is correlated with WM maintenance task in children until age 11 and for the later age groups after 11 years; it was correlated with the IC task. These results indicate that there is an increase in the inhibition of task irrelevant information as the age increases but not in the processing of task-relevant information. Shing and colleagues[63] conducted factor analysis to investigate at what age does WM maintenance and inhibitory control functionally gets differentiated. They found that both the processes are not distinct until age 9.5 after which they get differentiated. However, this does not inform if they do or do not interact during later ages, although a better ability for goal-directed behavior is only possible when both the processes mature. The three studies indicate that when there is an increase in WM load, inhibitory control gets affected; however, this effect decreases as the age increases.

Few researchers argue that working memory is only required to maintain the goal representations and the transitions in the development of cognitive control occurs due to the increase in the strength of working memory representations.[65] Arguing further, Wright, and Diamond[66] conducted a study by manipulating the order of congruent and incongruent conditions in hearts and flower task (combination of Simon and Stroop task). This manipulation varies the demands on control mechanisms as it requires maintaining the goal representation in terms of holding the rule (Simon task involves maintaining the rule and Stroop task involves manipulation of information) in mind to perform the task accurately. Results showed that on incongruent condition whether it comes before or after congruent condition, the performance was similar across all age groups (6–10 years). Irrespective of the order in which incongruent trials were presented, children in each age group performed slower and showed more errors on the incongruent condition. One way to explain this finding is that poor performance on incongruent trials could be due to the difficulty in maintaining the rule in WM. On the contrary one could also say that increasing demands on inhibitory control itself is sufficient to result in more errors and slower RTs in children hence supporting the dissociation between WM and inhibitory control as one of the processes closely related to executive attention. Inhibition of the competing information is achieved by greater recruitment of executive attention to focus one's attention on the relevant rule.[66]

The neuroscience models of working memory development have mostly relied upon clinical studies or neuroimaging studies with older children and adults.[67] However, some studies on working memory development in infancy have used Piagetian tasks and have shown lack of inhibitory control among younger participants and have attributed it to slow maturation of dorsolateral prefrontal cortex (DLPFC).[68, 69] With increasing age, higher levels of frontal–parietal and parietal-occipital EEG coherence were observed in the looking version of A not B search task among infants. This is consistent with studies on older children and adults showing the involvement of DLPFC, Intraparietal cortex, and posterior parietal cortex. Crone and colleagues[41] used the object working memory task and showed the involvement of DLPFC during the manipulation of items among children older than 12 years of age and adults. On the other hand, some researchers emphasize the role of medial temporal structures than PFC for working memory. They argue that emphasis on DLPFC for working memory is confounds the involvement of response inhibition processes in working memory tasks with actual WM processes.[70] This limitation could be addressed by taking a task, which minimizes the recruitment of response inhibition.[71] However, in children after 3 years of age, studies have shown the involvement of frontal–parietal network of working memory using functional Near Infra-red Spectroscopy in the visual object working memory task with increasing load as observed among adults.[72] Although there are a few studies on the early development of working memory in infancy, we have primarily discussed the developmental studies on younger and older children.

Thus, the interaction between WM and executive attention includes an investigation of many shared mechanisms including selection, target representation, distractor rejection, or inhibition. Developmental studies provide useful insight into some of these shared mechanisms of the two critical processes, earlier referred as executive functions along with certain other processes such as fluency, set shifting, and planning. Studies so far have shown protracted development of executive attention and working memory. Given that increase in WM demands may slow down the developmental progression of executive attention,[62] the demands on executive attention may also influence maintenance of information in WM. There need not be a complete dissociation between the two processes as some of the researchers have attempted to achieve by manipulating attentional demands in a working memory. The purpose of this line of research should be to understand the directionality of influence between WM and EA and other processes to use this information to develop effective learning strategies for children.

In one of our recent studies, we investigated the interaction between working memory maintenance and executive attention in a dual task paradigm among children (8 years = 28; 10 years = 29) and young adults ($N = 31$). A baseline flanker task (64 trials) with 50% congruent and 50% incongruent trials; a baseline working memory task (64 trials) with equal number of trials across the set sizes of 2 and 4; and a dual task

DLPFC: The dorsolateral prefrontal cortex (DLPFC) is an area within the prefrontal cortex involved in executive functions such as cognitive flexibility and working memory.

with 128 trials (50% congruent and 50% incongruent; 50% trials in set size 2 and 50% trials in set size 4) were conducted. Reaction times (RTs) and accuracy were measured for flanker task and accuracy for WM task. The flanker trial was considered as correct when the correct response was made on WM task and Flanker task (Fig. 1).

The results based on the baseline flanker task [3 (age: 8, 10 years, adults) × 2 (flanker type: congruent, incongruent)] with error rates and reaction time data showed improved performance with increasing age in terms of reduced conflict effect and less error rates. Error rates reduced with age on the baseline WM task. Data for dual task were analyzed to look at the effect of flanker congruence on the performance on working memory task as well as effect of working memory load on congruent and incongruent RTs and error rates. Results based on the dual task [3 (age: 8 years, 10 years, adults) × 2 (flanker type: congruent, incongruent) × 2 (set size: 2, 4)] with a significant three-way interaction, $F(2, 85) = 5.69$, $p = .005$, and post hoc results ($p < .05$) showed that increase in working memory load hampers the performance on the flanker task which required attention control to inhibit the distractors. However, the results based on the dual task with error rates on the working memory task as a function of flanker congruence and set size [3 (age: 8 years, 10 years, adults) × 2 (flanker type: congruent, incongruent) × 2 (set size: 2, 4)] did not show significant two-way (flanker type × set size), $F(1, 85) = .14$, $p > .05$, or three-way interactions (age × flanker type × set size), $F(2, 85) = 0.79$, $p > .05$. However, the main effects of age (decrease in error rates with age) and set size (increase in error rates with increasing set size) were significant ($p < .01$) (Figs. 2, 3).

Results based on the performance on working memory task showed higher error rates for set size 4 compared to set size 2 across all age groups for both single task and dual task (Fig. 4). Attention control is deployed in the flanker task and this deployment or efficiency of the attentional process improves as the age increases. Relationship between the working memory maintenance and the attention control was asymmetric in nature. Increase in working memory load hampers the performance on the flanker task, but parallel recruitment of executive attention does not affect memory maintenance. As per the time-based resource sharing (TBRS) model[21] of working memory, increase in cognitive load, which requires attentional control should affect the maintenance of items due to the increase in focus of attention. However, in our study, we found no effect of increase in demands on EA on working memory maintenance when greater attentional control was required on incongruent trials. It could be argued otherwise that fish flanker task requires less cognitive control compared to the other flanker tasks.[22, 73] According to the TBRS model, when cognitive

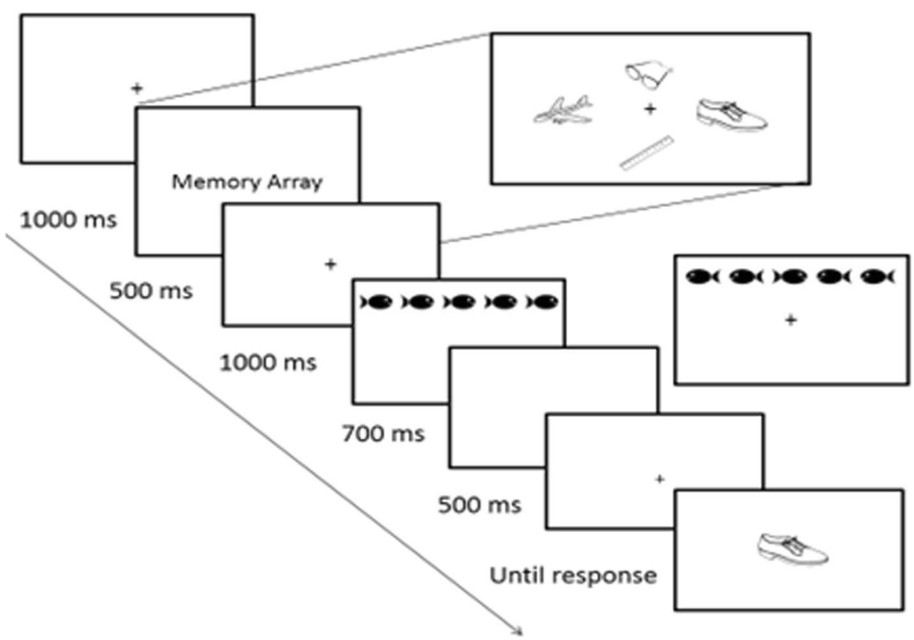

Figure 1: Trial structure of the object working memory maintenance task with sample stimuli.

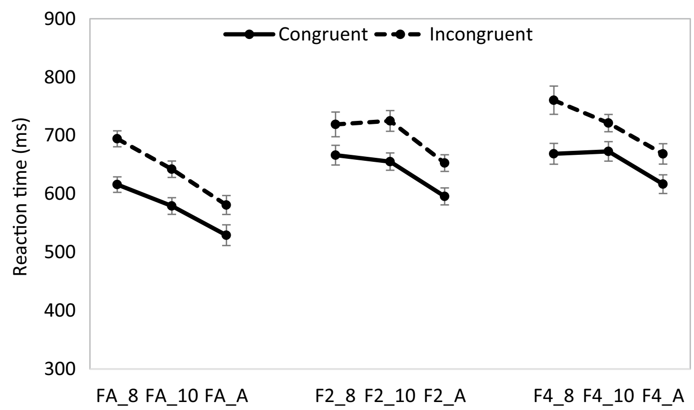

Figure 2: Mean comparisons of performance (reaction times) for congruent and incongruent condition on the flanker task (single and dual task) across the three age groups. FA_8: flanker alone (single task) 8 years age group; FA_10: flanker alone (single task) 10 years age group; FA_A: flanker alone (single task) adults; F2: performance on flanker task for set size 2; F4: performance on flanker task for set size 4.

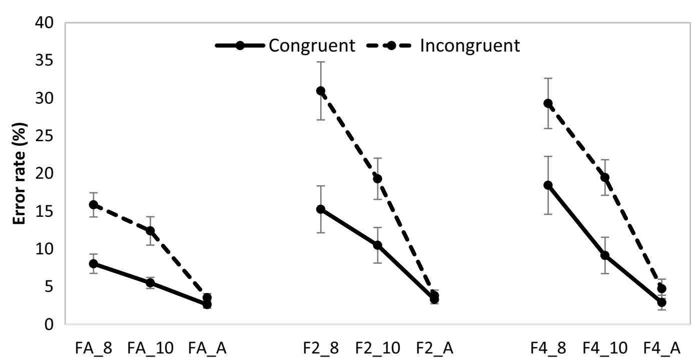

Figure 3: Mean comparisons of performance (error rates) on the flanker task in single- and dual-task condition across the three age groups.

load is less in terms of the demands on cognitive control, there is no effect of the conflict task on maintenance of items in WM. Working memory maintenance may play a role in minimizing distractor interference by maintaining goal-directed information. The two-way interference could be observed if the WM task involves manipulation in addition to maintenance. Given the evidences for the effect of working memory load and maintenance on executive attention, the shared mechanisms of the two processes could be critical for the cognitive demands related to learning.

3 Implications of the Interaction Between Working Memory and Executive Attention for Learning and Education

Working memory and executive attention is critical for many complex cognitive skills/activities including reasoning, planning, problem solving, language comprehension, reading, arithmetic, and self-regulation. These processes and skills play a key role in children's social adjustments and academic performance. Researchers have attempted to identify the early predictors of executive attention correlated with self-regulation and school competence.[74, 75] For instance, in a study on 12-year-old children, they were asked to perform a combined flanker-Go/No-go task, while EEG recordings were obtained. In addition certain measures of school competence and academic achievement were also used. Results showed that executive attention predicted most dimensions of school competence and event-related potential (ERP) amplitudes related to executive attention predicted academic achievement.[74] The field of education can gain insights from the research on how the brain develops and learns, mechanisms that underlie learning as well as the effects of age, cognitive functions, genetics, and environment on learning.[76] The field

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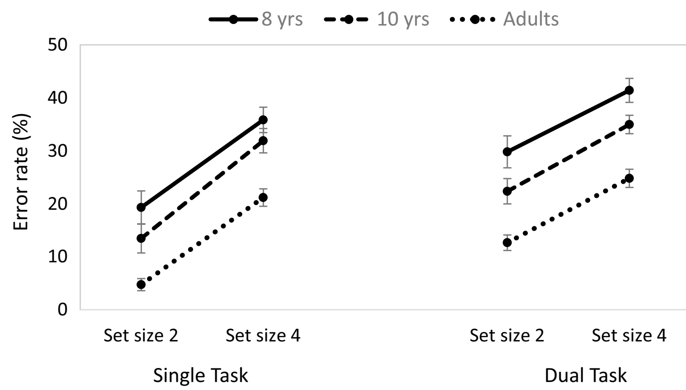

Figure 4: Mean comparisons of performance on the working memory task (single and dual tasks) as a function of set size and age.

of developmental cognitive neuroscience can influence educational practice and policy which requires in-depth understanding about how brain processes shapes, numbers, sounds, letters, and neural processes that underlie maintenance and manipulation of relevant information. It is believed that education changes the brain. Neuroscientists could inform the educators about neural mechanisms of plasticity and similarly educators could guide neuroscience research on learning and development. The cognitive skills, which regulate our thoughts and actions collectively called executive functions/self-regulation/cognitive control including working memory and executive attention. Moffit and colleagues[77] in their longitudinal study from birth to age 32 highlighted the importance of self-regulation in childhood resulting in less likelihood for dropouts in secondary school.

Development of language, literacy, numeracy, and attention has been reported to be fundamental for preparing children for success in school and this development starts as early as during infancy. Achievements of infancy could be well translated into the skills needed for success in elementary school and this depends on the development of the executive attention brain network.[78] Executive attention provides a means to develop complex cognitive skills including reading. Neural mechanisms for reading acquisition parallel the development of brain mechanisms associated with executive functions. Development of prefrontal cortex begins in infancy and continues until adolescence,[79] which parallels the development of executive functions such as working memory and executive attention.[80] By understanding the links between the development of reading-specific executive function networks, one could influence the rate of learning. Research has shown the effect of the development of executive functions on the development of prereading skills, word reading, and reading comprehension.[81] Working memory development has a significant impact on reading acquisition particularly reading comprehension. Similarly, executive functions and academic achievement are highly correlated. Since executive functions are modifiable environments can support their development and transfer the gains to academic achievement.[82] The interaction between working memory and executive functions particularly executive control could influence the acquisition of academic skills related to reading, numeracy, calculations, and comprehension of higher order information. Many studies have shown improvements in executive functions (working memory, cognitive flexibility and inhibitory control), but they have not been able to establish how specific or long lasting are these improvements. It should also be noted that training domain general or multiple cognitive skills might take longer to show benefits than one skill alone.[83] There is strong evidence for the links between academic outcomes, working memory, and executive control[84] and this interaction may be bidirectional. Enrollment in bilingual education programs may also result in executive attention-related benefits.[85]

Policy implications of scientific findings are related to the creation of learning environments and modifiability of neural networks, which may enhance the potential for continued growth in executive attention. This is as opposed to the intervention approach, which expects to show a far transfer from training in executive attention to academic achievement. It is difficult to find a far transfer of training in cognitive processes such as executive attention and working memory onto the learning mechanisms and achievement. Some environments constrain the development of executive functions including attention and working memory and some enhance their development. The current focus on structured learning of content, exams, and academic performance overrules the larger goal, i e., supporting cognitive development.[82] Hence, cognitive neuroscientists should be able to translate scientific research to real educational contexts by informing and involving the teachers in creating learning environments conducive for the development of working memory and executive attention.

To conclude, working memory involves processes such as attention, perceptual, and long-term memory representations. Working memory performance requires attentional control with increase in working memory load. Persistent activations in higher cortical regions such as prefrontal cortex and parietal cortex are necessary for maintenance and manipulation of information in working memory. It is also observed that maintenance and manipulation components of working memory may differentially get affected by the demands on executive attention or may call for the recruitment of executive attention. Development of working memory and attention is also closely linked during infancy as well as childhood. The cortical sources of working memory and executive attention overlap in terms of recruitment PFC shown with modulations in the negative central (Nc) ERP component and involvement of frontal and parietal areas in neuroimaging studies during infancy and early childhood as observed in older children and adults. Executive attention is particularly critical for working memory performance and the developmental transitions also overlap for the two processes. Hence, it is likely that the development of executive attention would influence the development of working memory and vice versa. Working memory functioning changes across the life span resulting in a protracted developmental trajectory and thus can be modified by training. Working memory may involve short-term plasticity yet fast synaptic changes as compared to the slower synaptic changes associated with long-term memory. On the other hand, training for executive functions in general and executive attention has shown improvements in academic performance in preschool children. If we understand the interactive role of the development of working memory and executive attention for learning and coping with increasing cognitive demands, effective strategies could be developed for faster and effective learning outcomes. This is not to say that other aspects of cognition including social emotional and other cognitive processes are not critical for better academic outcomes. Future work needs to look at the neural mechanisms underlying the unidirectional/bidirectional influence of the two processes on each other and test the specific implications of this interaction on learning and education.

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