THE LEARNING LEAD
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Nutrition and Executive Functions in Children

The ability to coordinate one's thoughts, feelings, and actions depends on the development of a specific set of cognitive processes responsible for cognitive control and purposeful and goal-directed behavior called executive functions (EFs).[1] As such, EFs are considered important building blocks for learning and creativity in children.[1,2]

EFs include three core, interrelated functions:

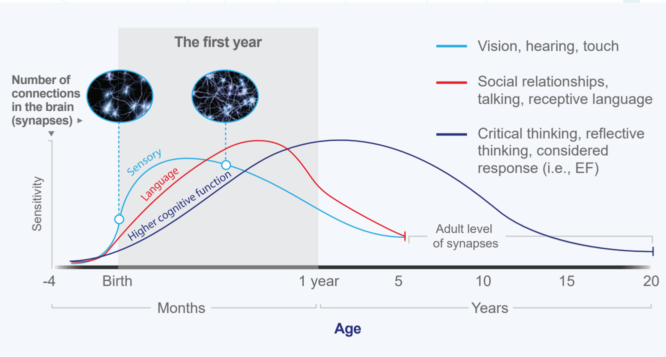
- **Inhibitory control:** Ability to suppress automatized or predominant responses, which allows one to focus attention and control or self-regulate behavior, thoughts, and emotions to override a strong internal response predisposition.[1]
- **Working memory:** Ability to update information while executing tasks, which involves holding multiple pieces of information in mind and mentally working with them.[1]
- **Cognitive flexibility:** Ability to switch between cognitive sets or tasks and flexibly adjust to changed demands or priorities.[1] Cognitive flexibility is closely linked to creativity as it is critical for seeing things from new and different perspectives.[1,3]

From these core functions, other higher-order cognitive processes can be built, including reasoning, problem-solving, decision-making, and planning.[1] These executive processes play an important role in many aspects of a child's behavior, learning, autonomy, and social and emotional skills.[1]

Development of EFs

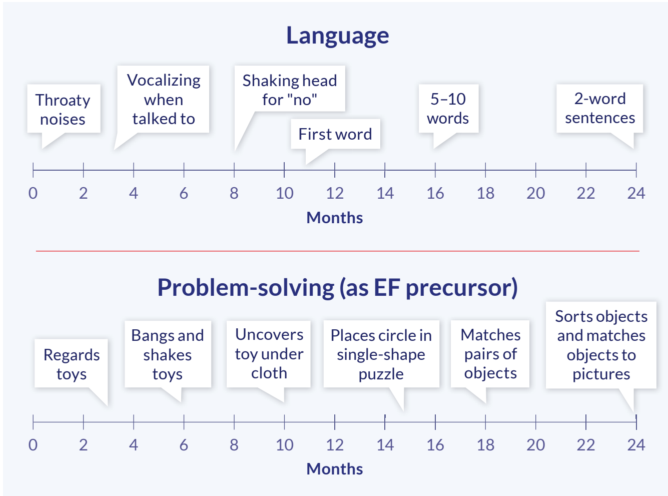
Generally, sensory, motor, and early language networks develop first in the brain,[4,5] laying the foundation to rapidly acquire skills in those developmental domains.[6] Higher-order cognitive skills, including EFs, draw on these earlier developing cognitive skills[4-6] (Figure 1). They begin emerging in early childhood and continue through adolescence.[7] The protracted development of EFs[8] relies on the connectivity and communication between brain networks,[5] particularly in later maturing frontal brain regions.[8,9]

Figure 1: Children's skill and functional development, including the development of EFs, parallels that of underlying brain networks and connections.[4,5] The successive developmental waves suggest that there are critical time periods for learning specific skills.[4,5]



When infants are born, some neurons have already formed brain networks that control vital functions, such as breathing and cardiovascular function,[10,11] or process sensory input.[4,5] New brain connections, networks, and their strength rapidly increase after birth[4,5] as maturation and experiences contribute to building a strong brain architecture.[12-14] As children grow and mature, brain connections continue to form and strengthen as needed to support more complex developmental skills,[10,15] as marked by the observable progression of milestones throughout early childhood (Figure 2).[16] Less used brain connections then begin a natural decline during childhood as the brain networks increasingly specialize.[20] Active connections reinforced by experience stabilize, while unused ones weaken or disappear.[20]

Figure 2: Examples of language and problem-solving (as EF precursor[1,2]) milestone development in the first 2 years of life from simple to more complex skills.[16]



Brain developmental processes, such as myelination,[17,18] influence the structure and function of brain connections (e.g., by facilitating information processing speed) and hence contribute to the ability to think, feel, and act.[19-21] The progression of myelination parallels the improvement of cognitive skills[22,23] and the acquisition of milestones in infants and children.[13,24] The relation between brain connections and EFs is bidirectional. As such, insults to myelination and connectivity can cause severe delays in the maturation of brain areas, resulting in delayed cognitive development.[25] Conversely, improvements in EFs have been found to correlate with increased myelination and synaptogenesis of the frontal brain regions in early childhood.[26,27] These regions are heavily involved in the control and coordination of higher-order EFs.[1]

Functional neuroimaging and electroencephalogram studies in preschool and school-aged children highlight the contributions of the frontal lobe, particularly the prefrontal cortex (PFC), as well as posterior and superior brain regions in the development of EFs.[28] Other studies have also demonstrated that the myelination of projections from the PFC to the striatum increases with age and is correlated with inhibitory task performance, indicating the growing functionality of the PFC for complex tasks.[8]

Role of Nutrition and EFs

In children, the development of EFs and underlying brain connectivity and myelination is influenced by a variety of factors—in particular, genetic, biological, individual, and environmental factors, including nutrition.[8,10,12,13,17,19,29,36] Neural maturation, schooling and education, language, social environment, and social connections (e.g., positive relationships with adults, physical and mental activity, practice, and creative play) can positively impact the development of EFs, whereas factors that disrupt the brain's architecture, negative stress, as well as neglect and violence can negatively impact it.[8,34-36]

Of the various factors that influence the development of EFs, nutrition is one of the most readily modifiable in young children.[37] The dietary intake of key nutrients in children has a significant role in providing the building blocks for the brain to create and maintain crucial connections,[4-6,20,30,38-41] including synapses and myelinated axons,[20] important for the development of EFs.[25-27] Clinical evidence supports the relation between EFs and the intake of the following key nutrients:

- **Iron** is a critical nutrient required for both myelination and synaptogenesis in addition to other neurophysiological processes, including neurotransmitter synthesis, cell division, and oxidative metabolism.[42,43] Studies have shown positive effects on selective attention with iron supplementation in anemic children (3–4 years).[44]
- **Omega-3 polyunsaturated fatty acids** are essential dietary nutrients for brain development as they play a central functioning role in brain tissue and affect many neurophysiological processes, including myelination, synaptogenesis, and neuronal membrane integrity.[25,38] Studies have shown positive correlations between outcomes of EFs in children 2–6 years and whole blood omega-3 fatty acids/docosahexaenoic acid (DHA).[45]
- **Zinc** is thought to be essential for EF-dependent brain development, with deficiency potentially interfering with neurotransmission and subsequent neuropsychological behavior.[46] Studies have demonstrated the importance of adequate zinc levels in children (10–16 years) for the promotion of executive and cognitive function, including improvement in visual memory and simple and recognition reaction times.[47,48]
- **Vitamin B_{12} and folate (vitamin B_9)** are fundamentally important for brain development due to their roles in myelination[49] and the synthesis of neurotransmitters.[50] Emerging evidence highlights the importance of these vitamins for EFs and cognitive performance throughout child development. One study has shown that children (10–16 years) with low vitamin B_{12} status performed significantly worse on an abstract reasoning test than those with normal status.[51] Another study reported a positive link between folate intake and academic achievement in children (15 years).[52] Though academic achievement does not directly assess EFs, there is ample evidence demonstrating the significant association between school performance and EFs.[53-56]

Executive functions, such as cognitive flexibility, self-control, decision-making, and problem-solving, are critical for many of the skills children need to succeed at school and in later life.[1] As one of the factors that influence EFs and their underlying brain connections—and related processes like myelination and synaptogenesis—in children,[8,10,12,13,17-19,29-36] nutrition may provide an effective way of promoting EFs.

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