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DEVELOPMENT OF GIFTEDNESS DURING EARLY CHILDHOOD

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Los niños con altas capacidades intelectuales (AC) parecen beneficiarse más de la experiencia que sus iguales sin AC desarrollando comportamientos cada vez más eficientes en entornos más complejos. La mayoría de los modelos que intentan explicar esta mayor adaptabilidad se centran en el estudio de las funciones cognitivas superiores y las regiones corticales que las sustentan, sin embargo, durante las primeras fases del desarrollo estas áreas son aún inmaduras funcional y estructuralmente. El objetivo de esta revisión es sintetizar y describir los mecanismos neurobiológicos subcorticales y corticales que subyacen a la interacción con el entorno, la motivación por la práctica y la automatización de los procesos cognitivos superiores en los niños con AC desde las primeras etapas de desarrollo postnatal.

Palabras clave: *Altas capacidades, Desarrollo, Cerebro, Aprendizaje, Subcortical: cortical.*

Gifted children seem to benefit more from experience than their non-gifted peers by developing increasingly efficient behaviors in more complex environments. Most of the models that attempt to explain this greater adaptability focus on the study of the higher cognitive functions and the cortical regions that support them. However, during the early stages of development these areas are still functionally and structurally immature. The objective of this review is to summarize and describe the subcortical and cortical neurobiological mechanisms underlying the interaction with the environment, which motivate the practice and automation of higher cognitive processes in gifted children from the early stages of postnatal development.

Key words: *Giftedness, Development, Brain, Learning, Subcortical: cortical.*

Gifted children constitute a highly heterogeneous group with common characteristics that differentiate them from their peers with average intellectual capacity. These children may devote a considerable number of hours and effort to certain domains and acquire exceptional skills at an earlier age than children of average abilities. In addition, they seem to progress rapidly in learning when the areas are of interest to them, they require minimal assistance and show great intrinsic attention and motivation. Research suggests that high performance is not simply a consequence of cognitive factors, but also factors such as motivation, practice, and task automation (Beckmann & Minnaert, 2018), which play perhaps an even more important role, especially in the early stages of learning. However, when attempts have been made to study the mechanisms underlying this increased efficiency in performance very few have included the vertical organization of the brain. One of the limitations of corticocentric approaches in the developmental context is that, due to the structural and functional immaturity of the cortex during early childhood, other subcortical processes, such as the basal ganglia and the cerebellum, become more relevant during learning (Koziol, Budding, & Chidekel, 2010).

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The aim of this work is to summarize and describe the neurobiological mechanisms that underlie the interaction with the environment, motivation to practice, experience, and task automation, as fundamental components of the learning process, during the early childhood of gifted children.

METHOD

The automated search of the bibliography was carried out using the Pubmed, Scopus, and Google Scholar databases. Principally, the keywords “gifted” or “talent” or “intelligence” and “brain” or “subcortical” or “cortical” or “motivation” or “dopamine” or “cerebellum” or “learning” or “developmental” were used without language restriction. Bibliographic reviews and empirical studies published in the last five years were included. From the titles and the abstracts, we selected the articles that met the objectives of this work, that is, those that directly related the learning process of gifted children to neurobiological aspects. Articles addressing giftedness in childhood from both a transversal and longitudinal perspective were included. The selected articles were analyzed in depth, and then indirect searches were carried out through the cited authors according to the relevance or novelty of the extracted data. Articles that did not provide any kind of neurobiological explanation, those that were not related to learning, and those focused exclusively on adults were excluded.

RESULTS

Of the selected articles, 68% directly address the specific psychobiological characteristics of gifted children and the remaining 32% refer to the functioning of the underlying neurobiological mechanisms cited in these articles that relate to learning during development.

Table 1 presents descriptive information on the studies included in this review in alphabetical order. The table includes the following: author(s) and year of publication, age of gifted subjects under study, and differential structural and functional neural characteristics with respect to subjects of average intellectual capacity.

Genetic and environmental influences

Intelligence is a complex behavioral trait and, as such, is highly polygenic, in the sense that many genes contribute to individual variation. Gene expression in the brain changes as a function of environmental experience during the time of development, so intelligence can be conceived as an emergent property that originates in multiple interactions between the limitations imposed by genes, the brain, behavior, cognition, and the environment.

TABLE 1
DIFFERENTIAL PSYCHOBIOLOGICAL CHARACTERISTICS RELATED TO LEARNING IN GIFTEDNESS

Author(s) and year of publication	Age	Structural characteristics	Functional characteristics
Alnæs, et al., (2018)	8-21 years old	Increased number of connections and activity within the medial cingulate-striated-thalamic-cortical circuit	Greater anticipation and sensitivity to reward during learning
Barbey (2018)	8-22 years old	Flexible and dynamic reconfiguration of the brain networks for fluid intelligence (frontoparietal regions of the executive system) Modification of the topology and community structure for the flexibility and adaptation of the whole system	Development of fluid skills: logical reasoning, cognitive flexibility, working memory.
Boot, Baas, Gaal, Cools, & Dreu (2017)	From 0 years	Moderate striatal dopamine levels and integrity of the nigrostriatal dopamine pathway Moderate prefrontal dopamine levels and the integrity of the mesocortical dopamine pathway Polymorphisms in dopamine receptor genes	Flexible processing Persistent processing Increased creative thinking, divergent thinking, and creative problem solving
Buttelmann & Karbach, (2017)	2-12 years		Increased cognitive flexibility and high metacognitive ability from preschool age
Chevalier, et al., (2015)	2-5 years	Increased myelin in the right and left occipital lobes, corpus callosum, and cerebellum	Increased speed of perceptual processing of visuo-spatial information
Dai, Müller, Wang, & Deoni, (2019)	0-3 years	*Increased speed in the myelinization process*	Improvement in general cognitive ability
Deoni et al., (2016)	*0-5 years*	Slower initial development during the first year of life (synaptogenesis), followed by a prolonged period of rapid maturation between 1 and 2 years of age (synaptic pruning)Increased myelination in corpus callosum, cerebellum, primary somatosensory cortex, right premotor cortex, and anterior cingulate	Improvement in fine motor function, visual processing, and receptive and expressive language skills
Dunst et al., (2014)	From 0 years	Integrity of white matter connections in the frontoparietal network In low/medium difficulty tasks: less energy consumption, less activation of the frontoparietal network and insula In difficult tasks: higher metabolic rates and increased activation in the lateral prefrontal cortex	Improvement in inductive reasoning tasks
Fiske & Holmboe (2019)	0-6 years	Stronger frontoparietal network of neuronal connections observed	Increased efficacy in working memory tasks, increasingly flexible and automated cognitive control

TABLE 1
DIFFERENTIAL PSYCHOBIOLOGICAL CHARACTERISTICS RELATED TO LEARNING IN GIFTEDNESS (Continuation)

Author(s) and year of publication	Age	Structural characteristics	Functional characteristics
Gómez-León (2019a)	From 0 years	High fiber density and optimally and evenly distributed brain networks Increased volume of the parahippocampal gyros and greater connectivity in the lower left parietal cortex region Thinner cortex and larger surface area in key regions of the frontoparietal networks and default mode	Increased cognitive fluidity and flexibility, abstract connection between concepts, production and understanding of metaphor, generation of creative ideas, creation of new uses for objects, episodic future thinking, and working memory
Goriounova & Mansvelder, (2019)	From 0 years	Pyramidal and striated neurons with larger and more complex dendrites Early maturation of the left frontoparietal network Increased brain volume of the temporal lobe and hippocampus and with the size and complexity of the pyramidal neurons in these regions	Faster action potentials, more efficient information transfer favoring neuronal plasticity and learning Improved ability in perception, language, working memory, reasoning, and general cognitive ability
Gotlieb, Hyde, Immordino-Yang, & Kaufman (2016)	Teenagers	Increased number of connections between the frontoparietal executive attention network and the default mode network	Creative exploration, intentional reflection, divergent social-emotional thinking: skills in considering multiple cognitive and affective perspectives, courses of action, and outcomes for themselves and others
Kaminski, et al., (2018)	From 0 years	Increased expression of genes regulating D2 dopamine receptors in striated neurons, increased volume in the striatum	Increased response to reward prediction signals
Khalil, Godde and Karim (2019)	From 0 years	Increased availability of dopamine in the ACC and prefrontal cortex, increased grey matter of these structures, and increased number of fibers binding them	Greater sensitivity and predictability to rewards, resistance to distraction, and perseverance
Koziol, Budding, & Chidekel, (2010)	From 0 years	Maturation of the frontostriatal circuits Increased number of connections between basal ganglia and cerebellum Increase in white matter tracts	Intrinsic motivation and perseverance Intuition and expertise Adaptation speed
Lee et al. (2006)	Teenagers	Significantly stronger regional activations of the upper group especially in the posterior parietal cortex	Improvement in fluid reasoning, attention control, and working memory
Lépine, Barrouillet, & Camos (2005)	11 years		Automate information more effectively
Liu, Xiao, Shi, & Zhao (2011)	10 years	Evoked potentials: stronger P50 suppression in the frontocentral area, stronger N100 suppression in the frontal and frontocentral areas, more efficient N2 activations during conflict monitoring processing, faster P3 responses over frontal regions, and stronger P3 activations over central-parietal regions during attention control processing	Better inhibition control Increased sensory activation Improved conflict control performance, with greater accuracy, and faster response speeds
Montero-Linares, Navarro-Guzmán, & Aguilar-Villagrán (2013)	6-9 years old	Functional specialization of the left posterior parietal cortex	Less dependence on attention resources for sequencing and execution of procedures
Nusbaum, et al. (2017)	8-12 years old	Increased intra- and interhemispheric distribution of white matter: ascending fibers from thalamus and descending fibers from frontoparietal cortex to subcortical nuclei), uncinate fascicle, upper longitudinal fascicle Increased volume in genu and splenium of corpus callosum	Subjects with left hemispheric lateralization: Heterogeneous IQ, superior verbal index Subjects with bilateral and right hemispheric lateralization: homogeneous IQ, overall scanning, processing, and environmental adaptation capabilities

TABLE 1
DIFFERENTIAL PSYCHOBIOLOGICAL CHARACTERISTICS RELATED TO LEARNING IN GIFTEDNESS (Continuation)

Author(s) and year of publication	Age	Structural characteristics	Functional characteristics
			Improved attentional and inhibitory control, memory, and language High-level transfer of semantic information
Rinaldi and Karmiloff-Smith, (2017)	From 0 years	Greater plasticity over a longer period of time More efficient neural activations, using fewer neural resources, and consuming less energy Early shift from distributed processing to more localized processing Highly integrated global and local brain networks Increased grey matter, in the sensorimotor and visual cortex	Early development of attentional and sensory-motor systems Increased capacity to process information measured by visual habituation and selective attention to novelty 6-12 months Efficient use of executive functions, adapting more efficiently to the demands of the environment More efficient and early development of attentional and sensory-motor systems from the early post-natal days
Santarnecchia, Emmendorfera, & Pascual-Leone (2017)	From 0 years	Increased number of connections between neocortex, basal ganglia, and cerebellum	Flexibility and cognitive adaptation Coexistence of automated actions and others of higher order executive control, favors experience and talent
Sastre-Riba, Viana-Sáenz (2016)	8-15 years	Increased interhemispheric and inter-area connectivity, especially in the frontoparietal regions, and in the cerebellum	Ability to make intuitive discoveries in areas of adaptation not based on instrumental or categorical learning
Sastre -Riba & Ortiz (2018)	From 0 years	Activate alpha waves more frequently, selectively activate brain areas especially linked to the task Earlier frontal lobe maturation and myelination, with resulting higher neuronal density Interhemispheric interconnectivity Increased persistent bilateral activation of the prefrontal and frontoparietal cortex Increased neural resources for automatic processing before frontal activation	Faster processing Better working memory, high level of abstract thinking and creativity Greater potential for convergent and divergent thinking Facility for faster learning that requires less repetition, with greater depth, abstraction, creativity, and sensitivity Better cognitive control (or executive regulation)
Schnack et al., (2015)	9-60 years	Reduced cortical thickness in the main areas of association (frontal, temporal, and parietal) Increased expansion of the cortical surface, completed at an earlier age	Increased functional specialization and improved executive functions
Shi et al. (2013)	10 years		Increased sustained attention, inhibitory control, and metacognitive skills
Steiner & Carr, (2013)	0-12 years		They get used to stimuli earlier and prefer new stimuli during the first year of life
Vaivre-Douret, (2011)	From 0 years	Volume of the prefrontal cortex and cerebellum Increased number of connections between the cerebellum and areas of the frontal and parietal lobes	Increased cognitive skills scores Early and efficient use of executive functions: planning, cognitive flexibility, inhibitory control, working memory

The genes associated with educational achievement and intelligence are expressed preferentially together in the nervous tissue (Gómez-León, 2019b). Ninety-five percent of these genetic variants are found in regions that could have a regulatory function for gene expression and synaptic communication throughout development (Goriounova & Mansvelder, 2019). Therefore, many of these genes could play a role in neurological development by contributing to synaptic function and plasticity through a highly dynamic process that depends on the interaction of the subject with his or her environment and is reinforced by experience (Deoni et al., 2016).

Most behavioral phenotypes do not emerge at a particular point in time, but gradually, through the cumulative effects of factors that influence them throughout the individual's life. The heritability of general cognitive function increases linearly from 40% in childhood to 80% in adulthood. This genotype-environment correlation suggests a genetic modulation of environmental influences on cognition, i.e. as children grow older, they increasingly select, modify, and even create their own experiences, in part, based on their genetic tendencies (Goriounova & Mansvelder, 2019).

They have greater neural plasticity

Neural structure and function change dramatically during the early postnatal period. Acquiring a new skill involves temporary and selective structural and functional changes in the neurons of the areas of the brain involved in processing that skill. Recent studies have shown that these changes are more pronounced in people with giftedness (Nusbaum et al., 2017), who have large and complex dendrite neurons capable of transferring information more efficiently, favoring neuronal plasticity and learning (Goriounova & Mansvelder, 2019; Gómez-León, 2019a). Modifications in dendritic morphology and synapses produce variations in the volume of cortical gray matter. The greatest changes observed during the first year of life are in the cerebellum, followed by other subcortical brain regions such as the basal ganglia and finally in regions within the cerebral cortex where gifted children follow a different pattern of change than their non-gifted peers, showing a particularly plastic cortex with early and prolonged development (Fiske & Holmboe, 2019; Schnack et al., 2015).

Neural circuits that maintain attentional functions, motivational interest, and the rehearsing or practicing of new learning mature before the circuits and networks that support higher cognitive processes. The development of these circuits has been correlated with the development of cognitive and behavioral functions in gifted children (Koziol et al., 2010).

Their processing speed is higher

The speed of information processing, due to increased myelinization, is critical during a child's cognitive development since it improves the propagation of the neural impulse, facilitates the rapid and error-free transmission of data between different regions of the brain, and allows for the manipulation of a greater amount of more complex information in less time (Deoni et al., 2016).

During the first 2-3 years of life, a rapid process of myelinization and axonal packing begins, which will continue more slowly during childhood and predicts overall cognitive ability (Deoni et al., 2016; Lebel & Deoni. 2018). Subcortical brain regions achieve myelination earlier than regions involved in higher cognitive functions such as the prefrontal cortex (PFC). The cerebellum, protuberance, and internal capsule are some of the first structures to myelinate, the occipital and parietal lobes do so at about 4-6 months, and the frontal and temporal lobes at about 6-8 months (Fiske & Holmboe, 2019). Within the frontal lobe, the orbitofrontal cortex (OFC), which is related to emotions, reaches structural and functional maturity at an earlier age than other regions of the PFC.

The myelinization profile of white matter in the first 5 years of life is strongly and specifically related to cognitive ability (Fiske & Holmboe, 2019). Between 12 and 24 months the general cognitive capacity is diffusely associated with the structure of the brain, but specialized networks and discrete brain circuits are already observed. Examples include the non-verbal function associated with regions of white matter in the cerebellum, corticospinal tracts, and motor cortexes; and the verbal function associated with the supramarginal gyrus and temporal lobe. Between 2 and 5 years the structure-function relationship seems to consolidate, in this period the associations become more localized and specific. In particular, changes in the left frontoparietal network are significantly associated with cognitive ability in childhood. This network is associated with the capacity of perception, language, working memory, reasoning, and general cognitive capacity (Goriounova & Mansvelder, 2019).

Using a longitudinal design in conjunction with advanced magnetic resonance imaging, it has been shown that children with above-average capacity show differential developmental trajectories of myelin compared to children with average and below-average capacity, even when controlling for socioeconomic status, gestation, and birth weight (Dai, Müller, Wang, & Deoni, 2019). Specifically, higher capacity children exhibit slower but more prolonged early development, resulting in an overall increase in myelin measurements by approximately 3 years. These results are consistent with those found in the grey matter volume and provide new insights into early neuroanatomical correlates of cognitive ability, suggesting that a period of prolonged early plasticity associated with white matter may result in strengthened neural networks that can better support later development. This slower development may allow for greater environmental interaction and fine-tuning of neural systems, and there may be a symbiotic relationship between cognitive capacity and cortical development (Dai et al., 2019: Deoni et al., 2016).

They interact more with the environment

From the first postnatal days, the newborn responds to the environment, so it actively participates in the development of its own neural substrate generating new neural connections and circuits (Jeremy & Schmahmann, 2019). The sensory and motor skills are fundamental for interacting with the environment and adapting successfully. Gifted children, compared to those who are non-gifted, show a more efficient and early development of the attentional and sensorial-motor systems from the first postnatal days, which is an advantage in the organization and consolidation of the basic cognitive processes that will support other more complex ones (Rinaldi & Karmiloff-Smith, 2017). In general, this greater efficacy runs parallel to the increase in the connections of the gray matter, especially in the sensorimotor and visual cortexes and the myelinization of the association areas that are developing at that time (Nusbaum et al., 2017).

The findings support an association between myelin and the speed of perceptual processing of visuospatial information in children aged 2 to 5 years. Shorter inspection times, after controlling for age, are associated with increased myelin in the right and left occipital lobes, corpus callosum, and cerebellum (Chevalier, et al., 2015). The strongest link is found in the left occipital lobe and has been associated with rapid naming of images and access to lexicon in school-aged children, perhaps reflecting faster access of language networks to visual information; language skills predict giftedness from 12 months. At these ages, myelin in the frontal and parietal regions of the brain has also been significantly associated with processing speed (Chevalier, et al., 2015).

But gifted children not only respond earlier and more efficiently to sensory stimuli; they also get used to them sooner and prefer new stimuli. These children's preference for novelty during the first year of life predicts the scores obtained in intelligence tests taken years later (Rinaldi & Karmiloff-Smith, 2017; Steiner, Carr, 2013). The medial temporal lobe allows for the processing and analysis of sensory-perceptual information from experiences to be retained for later problem solving. This system of declarative/episodic memory allows the persistence of sensory-perceptual and ideational experience, which represents an obvious adaptive advantage for problem solving. Different neuronal circuits that are functionally linked to the hippocampus participate in the regulation of memory in the face of novel stimuli, such as the amygdala or the prefrontal cortex that receives projections from the locus coeruleus (LC) and modulates the levels of noradrenaline (NA) and dopamine (DA) (Hansen, 2017).

It seems that intelligence is significantly correlated with the brain volume of the temporal lobe and the hippocampus and with the size and complexity of the pyramidal neurons in these regions (Goriounova & Mansvelder, 2019). The hippocampal pyramidal neurons are critical for the retention of novel stimuli. The more intense burst firing of gifted children in the LC may be associated with an increase in DA and, consequently, with an increase in synaptic strength and plasticity of hippocampal neurons that promotes long-term memory (Duszkiewicz, McNamara, Takeuchi, & Genzel, 2019, Wagatsuma et al., 2018). This would explain why they not only recognize novelty earlier (Steiner & Carr, 2013) but also process it more efficiently (Berger, Tzur, & Posner, 2006).

They are more sensitive to rewards

The cognitive performance of children with giftedness may be influenced by genetic variants that modulate task motivation. These genetic variants participate both directly in synaptic modulation and through modifications produced by achievement, i.e., by task repetition. It has been suggested that the greater anticipation and sensitivity shown by children with giftedness to reward during learning may be due to increased activity within the medial cingulate-cortico-striatal-thalamic circuit (Alnæs, 2018). Within the striatum, learning is mediated by DA which acts on medium spiny neurons improving or facilitating transmission along the direct thalamo-cortical pathway.

A recent study has found that cognitive performance is significantly associated with increased expression of genes regulating dopamine D2 receptors in striatal neurons (involved in inhibiting competitive cortical signals), increased striatal volume, and increased response of the striatum to reward prediction signals (Kaminsk et al., 2018). On the other hand, the number of connections linking the cortex to areas associated with reward anticipation, such as the striatum, is greater in gifted children than in those of average intellectual capacity (Alnæs et al., 2018), which would help explain some of the essential characteristics of these children, such as intense focus in certain areas, intrinsic motivation to master them, resistance to distraction, and perseverance. It has been suggested that environmental conditions act genetically to cause greater sensitivity and predictability of rewards (Boot, Baas, Gaal, Cools, & Dreu, 2017; Kaminski et al., 2018) and early maturation of frontostriatal pathways (Khalil, Godde, & Karim, 2019).

They show a greater interest in the task

The early interest these children show in certain activities may be stimulated by the expectation of success gained through participation in that activity or others from their experience. The perception of self-efficacy that guides the behavior of gifted children may be influenced by the increased availability of dopamine in the anterior cingulate cortex (ACC) and prefrontal cortex, the increased gray matter in these structures, and the increased number of fibers that bind them together (Buttelmann & Karbach, 2017). The ACC has been shown to be functional in children with giftedness at the age of 3, which allows them to plan and evaluate challenges based on their previous experience, unlike non-gifted children. This ability is associated with increased metacognition (Buttelmann & Karbach, 2017; Chevalier & Blaye, 2016).

Involvement of the cortico-basal ganglia-cerebellar network during learning

Computationally, the cerebral cortex, basal ganglia, and cerebellum have been hypothesized to implement different learning processes. Unsupervised learning takes place in the cortex where synaptic connections are reinforced by the repeated activation of the most efficient synapses. The basal ganglia are generally associated with reward-(reinforcement-) based learning, and the cerebellum is associated with error-based learning (Wang, Kloth, & Badura, 2014). Usage-dependent, reward-based, and error-based supervised learning requires the operation of an integrated mechanism that gradually guides performance. Recent findings show that the basal ganglia and cerebellum are interconnected at the subcortical level and thus form an integrated network. This network is organized topographically so that the motor, cognitive, and affective territories of each node in the network are interconnected (Sokolov, Miall, & Ivry, 2017).

Instrumental learning in children with giftedness

Several anatomical and functional neuroimaging studies have shown that the orbitofrontal cortex, the anterior cingulate, and the corpus striatum (caudate and putamen) exert major influences on the way frontostriatal circuits related to instrumental learning are developed. The early maturation of these circuits in gifted children explains many of the characteristics that define them (Koziol, Budding, & Chidekel, 2010).

When a high level of competence is acquired through experience, such as that which gifted children can achieve, the "pre-decision stage" that precedes awareness of a solution seems to be mediated preferably by the basal ganglia, temporal regions, and parietal circuits as part of an automatic process of instrumental learning by categorization that is not under conscious control and that enables the selection of actions through an "evaluation" of environmental reinforcements. Immediate feedback, or instrumental reward based on DA, plays a critical role in facilitating this type of procedural learning (Beckmann & Minnaert, 2018). Practice and experience increase the speed and accuracy of response, making categorization an "intuitive" experience. In this process the cerebellum regulates the speed, intensity, and rate of input it receives, and intensifies the valence with which that reward is experienced through its basal ganglia projections. In this way the cerebellum promotes practice through two mechanisms: increasing the valence associated with the stimulus and promoting success and effectiveness.

Error-based learning in gifted children

Gifted children not only progress rapidly within their domain(s) of choice, they also seem to make "discoveries" or show unusual intuition. The nature of this intuition has been studied on numerous occasions (Jeremy & Schmahmann, 2019; Wang, Kloth, & Badura, 2014). Certain intuitive abilities appear to be fundamentally mediated by the basal ganglia, while others appear to be based preferentially on control of the cerebellum.

It has been proposed that the cerebellum plays a key initial role in processing external sensory and internal information to guide the refinement of neocortical structures during developmental sensitive periods. Thus, the cerebellum acts in early life to shape the function of other regions of the brain, especially those related to language, cognition, and affect (Wang et al., 2014).

The cerebellum grows during a period of known genetic and environmental vulnerability and reaches maturity within a few months of birth. This structure functions as a corrective system capable of anticipating, preventing, and rectifying errors that may occur in behavior, whether motor, cognitive, and/or affective, allowing the improvement of skills already acquired or the acquiring of new skills that are more efficient and adaptable, especially in behavior related to novelty, observation, and flexibility (Sokolov et al. , 2017)

Gifted children have greater inter-hemispheric and inter-area connectivity, especially in the frontoparietal regions, and in the cerebellum (Sastre-Riba, Viana-Sáenz, 2016). These children often demonstrate the ability to make intuitive discoveries in areas of adaptation not based on instrumental learning or categorization, and it is in these areas that the cognitive functions of the cerebellum become especially relevant. The prefrontal cortex, along with the appropriate parietal and/or temporal cortexes, are activated when the individual establishes a conscious "model" of the problem within working memory. Brain-cerebellar circuits copy the contents of this working memory into the cerebellum, which is operating outside of consciousness, creating internal models of response. These internal models are a representation of environmental states and statistically efficient responses based on experience. The cerebellum sends this information to the prefrontal cortex through cortical-cerebellar feedback, activating and anticipating possible future solutions, at this moment the solution, or what has been called intuition, is made conscious by increasing attentional control (Jeremy & Schmahmann, 2019). The cerebellum receives information about the selected response and its real efficiency in the immediate environment through the feedback it receives from the cortex, so it quickly rectifies errors with great temporal and sequential precision in order to increase the accuracy and efficiency of the response. Everything that is thought of repeatedly is constantly improved through new modeling that results in increasingly fast and efficient, or intuitive, solutions, so that the cerebellar circuits are continually being reconstructed. In this way gifted children initiate and accelerate a positive feedback loop with the cerebellum in a specific knowledge domain. The maintenance of these synapses is enhanced by increasing the connection between the cortex and the cerebellum, especially in the prefrontal dorsolateral regions, supporting the role of the cerebellum in relation to the maintenance of working memory, problem solving, and executive functions. Several studies have found a correlation between IQ and the volume of the prefrontal cortex and the cerebellum, as well as between IQ and the increased number of connections between the cerebellum and the frontal and parietal high-level planning and thinking areas (Vaivre-Douret, 2011).

Social Learning in Children with Giftedness

The ease of attending to socially salient stimuli in gifted children may be related to the greater sensitivity they show towards the reward of stimulation (Alnæs et al., 2018), but also to the greater involvement of the cerebellum in the accurate representation of temporal information. Thus, the role of the cerebellum may also be of great importance for social learning. In both language and social development, the juxtaposition of multi-sensory events occurring on short time scales provides meaning and requires the integration of a variety of non-verbal signals and statistical learning (Sokolov et al., 2017). The cerebellum allows for the detection of very close and rapid time associations between multisensory stimuli and intrinsically rewarding stimuli, such as the mother's smile, which in principle would have no emotional value, and food or touch, which are intrinsically pleasurable. Similarly, simple exposure to language does not facilitate the development of speech and language if it is not accompanied by socially rewarding information that attracts the child's attention (Gómez-León, 2019a). Speech is a complex sensorimotor skill and vocal learning involves both the basal ganglia and the cerebellum (Pidoux et al., 2018) so the greater number of connections between the two structures in gifted children may facilitate learning and a more rewarding and enriching environmental exchange.

They automate information more effectively

Some authors point out that these reciprocal relationships between the neocortex, the basal ganglia, and the cerebellum respond to the flexible and effective mode of adaptation that gifted children have, allowing the coexistence of automated actions that alternate with others under the executive control of higher order, providing the opportunity for the development of experience and talent (Santarnecchia, Emmendorfera, & Pascual-Leone, 2017). The cerebellum can play a complementary functional role to the neocortex in consolidating memory by allowing rapid adaptation in the cerebellar connections along with gradual plasticity in the cortical areas where memory is stored. Experience with one problem facilitates performance on another problem without subjects being aware that one has helped solve the other. Therefore, changes in the cerebellum can, over time, drive changes in the corresponding cortical areas, increasing the efficiency of information processing, including the speed and consistency of perceptions and decisions, the speed with which new skills are learned, and the regulation and automation of behavior (Badura et al., 2018; Rinaldi & Karmiloff-Smith, 2017; Wang et al., 2014).

Children with high abilities automate information more effectively than those of average intelligence, which gives them an initial advantage that facilitates the handling of information in more complex thought processes (Lépine, Barrouillet, & Camos, 2005). Knowledge automation allows us, on the one hand, to have a more complex representation of the problem and, on the other hand, to free up attention resources that can be used for other more difficult processes, increasing success in the task (Montero-Linares, Navarro-Guzmán, & Aguilar-Villagrán, 2013). Using neural network modelling, it has been shown that the greater efficacy in working memory tasks in these children is related to a frontoparietal network of stronger neural connections observed from about the age of 4 (Fiske & Holmboe, 2019). At this age non-gifted children reflect a more diffuse global cortical activation in the frontal cortex, parietal cortex, corpus striatum, and cerebellum with more efficient processing as they get older, suggesting that non-gifted children need to participate in compensatory neuronal activation to achieve the same level of performance. In comparison, gifted children show a decrease in activation of the caudate and thalamus that may indicate a process of refinement in the frontoparietal regions, which allows for greater engagement and more efficient functioning of these circuits in increasingly difficult situations that depend on executive functioning (Benedek et al., 2016; Dunst et al., 2014; Lee et al., 2006).

The increased functional connectivity between the frontal and parietal regions leads to increasingly flexible and automated cognitive control, such that in working memory tasks age correlates negatively with activity levels in the dorsolateral and ventromedial prefrontal cortex and the hippocampus, but positively with the left posterior parietal cortex (PPC), which leads to the proposal that greater experience is accompanied by functional specialization of the PPC together with less dependence on attentional resources for the sequencing and execution of procedures (Montero-Linares et al., 2013). Frontal activation is related to a more controlled cognitive activity that requires more effort and higher energy consumption, occurring mainly at the limits of the system's capacity, as is the case with working memory. Posterior activation is related to more automatic perceptual processing below capacity limits (Benedek et al., 2016). It has been shown that gifted children, on tasks of equal difficulty as their non-gifted peers, make greater use of their automatic neural resources prior to controlled frontal activation, favoring a working memory that is, in addition, more efficient. This lower mental effort in subjects with giftedness is also evidenced by the lower metabolic consumption in identical tasks, corroborating that their neuronal circuits are more efficient (Barbey, 2018, Dunst et al., 2014; Lee et al., 2006). When confronted with more difficult tasks, activation of the dorsal lateral prefrontal cortex, related to working memory and planning, is greater than that of their non-gifted peers, recruiting a greater number of regions related to the specific characteristics of the task and showing a functional advance with respect to their non-gifted peers, of 3 years on average (Vaivre-Douret, 2011).

Executive functions and academic performance in gifted children

The developmental trajectories of the executive functions in gifted children are thought to be inextricably linked to changes in the maturation of the prefrontal regions and associated cortical and subcortical structures, including the parietal regions and basal ganglia, facilitating the development of a range of skills such as cognitive flexibility, inhibition, working memory, and metacognition (Rinaldi & Karmiloff-Smith, 2017, Sastre-Riba & Ortiz, 2018; Shi et al., 2013). These skills allow gifted children to regulate and direct their thoughts and actions flexibly towards adaptive and goal-directed behavior at an earlier age than normotypic children.

Gifted children perform better on tasks that require cognitive control. Early improvements in inhibitory control enable the individual to inhibit environmental interference and unnecessary impulses, promoting sustained and endogenous attention. This type of attention is more dependent on the individual's effort and ability to self-regulate, is goal-directed (Liu, Xiao, Shi et al., 2013), and can predict performance on cognitive tasks (Shi et al., 2013).

Greater cognitive flexibility in gifted children reduces errors of persistence with flexible rule tasks and attentional change, compared to non-gifted children (Vaivre-Douret, 2011). These differences are observed from age 3 and appear to be due to both the use of strategies related to metacognition and the ability to maintain and select tasks in working memory (Vaivre-Douret, 2011). The use of metacognitive strategies mainly reflects qualitative changes in information processing, such as the conceptual understanding of the hierarchical rule system underlying the tasks.

The use of these skills favors a change in the combination of strategies used in solving problems with great implications for academic performance. In any domain studied, when a skill begins to develop it requires the use of relatively slow and error-prone procedures, while the practice of that skill results in relatively fast and accurate memory-based processes. The level of experience produces a modulating effect on the functional specification of the PFC and modulates the white matter architecture of the brain, recruiting a frontoparietal network of long-range connections that participates with other brain regions in a divergent way. These skills favor problem-specific responses that would lead to less use of procedures and more use of memory, increasing efficiency in problem solving (Jeon, Kuhl, & Friederici, 2019).

Research suggests that academic achievement is dependent on a wide range of strategies, skills, attitudes, and behaviors that play an essential role in academic performance, but which cannot be captured (directly) by cognitive or performance tests (Beckmann & Minnaert, 2018). These include metacognitive skills, motivation, self-esteem, creativity and personality traits.

Common characteristics that favor learning in gifted students not directly measured by cognitive tests include the following: advanced vocabulary use, high creativity, strong critical thinking skills, task engagement, high levels of motivation, coping skills, and perseverance (Beckmann & Minnaert, 2018). Early maturation of the frontostriatal circuits in these children (Alnæs et al, 2018; Kaminsk et al.,2018, Khalil et al., 2019, Koziol et al, 2010) could favor these characteristics and, consequently, academic performance. However, when these students do not benefit from the support of parents, teachers and/or peers, and/or when their academic and other needs are not met, this same mechanism could negatively impact their academic performance through negative emotions and attitudes, disruptive behavior, poor motivation, low self-esteem, unrealistic expectations, and adverse interpersonal relationships (Beckmann & Minnaert, 2018).

CONCLUSION

Different studies have shown the greater effectiveness of gifted children not only in detecting novelty but also in adapting to it by acquiring automated behaviors more quickly and accurately than their non-gifted peers. These children organize and store large amounts of information in the long-term memory, often showing effortless processing of knowledge relevant to their areas of expertise to which they have quick and reliable access.

When studying the neurobiological mechanisms underlying learning during early childhood in gifted children, the main objective of this review, it is observed that gifted children have large and complex neurons capable of transferring information more efficiently, favoring neuronal plasticity (Goriounova et al., 2019). A brain more sensitive to stimulation and reward not only captures more intensely, but also encodes and stores more intensely and efficiently. All deliberate practice, or repetitive working memory, is located in the prefrontal networks and is "copied" and mediated by the cerebellum, which uses "internal models" of the environment to carry out supervised learning outside of the conscious control. The cerebellum specializes in the modulation and hierarchization of certain domains, favoring the efficacy and success of action. The achievement of the practice generates an increase of dopamine that is captured by a system that, in turn, is unusually sensitive and that is reinforced by the efficacy of its own practice. This ability to experience emotions early and intensely, in an especially plastic brain, allows the neural connections for the skill in question to develop earlier and more quickly. Greater development of the anterior cingulate cortex allows the present situation to be assessed on the basis of past achievements, increasing the readiness for new challenges. In this way gifted children benefit more from experience by developing increasingly efficient behaviors in more complex environments. The automation of some behaviors and the adaptation of others allows the integration of more knowledge than is already available by interacting more effectively with the environment. Therefore, in gifted children, continued practice and early maturation of the frontoparietal and frontostriatal circuits may allow for more complete and consistent recruitment from these regions and greater use of automated strategies in performing tasks with increasing difficulty at earlier ages (Buttelmann & Karbach, 2017).

Gifted children perceive, process, and respond to the environment differently, so the full development of their potential and the underlying neural structures likewise require different intervention. The exceptional performance that gifted children can exhibit not only depends on repeated practice, but also on a system capable of quickly adapting and efficiently processing a growing amount of increasingly complex information. It has been shown that the same training in metacognitive strategies does not have the same effects on children with and without giftedness, with the latter benefiting more (Chevalier & Blaye, 2016; Buttelmann & Karbach, 2017). The practice needed to achieve high performance in gifted children and adolescents requires contexts that foster intellectual curiosity and the development of social and emotional imagination (Gotlieb et al., 2016).

In the educational context, gifted children often face tasks that are monotonous and repetitive for them, in which they have to direct their attention to external stimuli, without personal relevance, so they sometimes feel unmotivated and lose all interest in the academic environment. Research suggests that the development of giftedness should be fostered from early childhood through new and challenging tasks and environments that allow for reflection, the connection of school work with a broader purpose, intellectual curiosity, and the development of social and emotional imagination, in short, through environments that favor investigative, critical, and creative thinking (Gotlieb, 2016).

This review, despite presenting the data in a simplified manner, aims to motivate research that considers the genetic-environmental correlations that occur when children actively or passively seek and choose experiences based on their characteristics and genetically influenced motivations. The data presented suggest the need to create educational programs adapted to the characteristics of gifted children from early childhood, programs that link emotional and motivational arousal with activities designed to exercise and promote selective attention or the executive functions.

CONFLICT OF INTERESTS

There is no conflict of interests.

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