***Abstract***

Attention Deficit Hyperactivity Disorder (ADHD) is a neurodevelopmental disorder characterized by inattentiveness, hyperactivity, and impulsivity. Symptoms of ADHD are classified as either Inattention or Hyperactivity/Impulsivity. Inattention symptoms include carelessness, distractibility, easily sidetracked, disorganization, misplaces necessary items often, and forgetfulness. Hyperactivity symptoms include restlessness, impulsivity, impatience, intrusiveness, inability to play quietly, and excessive talking. Symptoms usually start in childhood and may persist into adulthood if left untreated. The DSM-5 revised the ADHD diagnostic criteria regarding symptoms, age of onset, and symptom exclusivity. The number of symptoms required for diagnosis in either category (inattention or hyperactivity) has been reduced from 6 to 5 for older adolescents/adults. Age of onset has raised the age limit for initial symptom onset from 7 to 12. ADHD is often treated with medication, therapy, or a combination of both to help manage the symptoms and improve daily functioning for affected individuals. There is a rapidly growing body of research regarding all aspects of ADHD, both in the basic and clinical sciences. The goal of this review is to compound this information, including the anatomy, pathophysiology, and clinical presentations of ADHD.

***Background***

***Prevalence***

***Causes (Genetics, Environment, Development Course)***

***Risk Factors (Family History, Prenatal Nicotine Exposure, Fetal Alcohol Syndrome, Prematurity)***

***Complications***

***Comorbidities***

***Treatment***

***Anatomy***

***Amygdala***

The amygdala, which is located within the limbic system, is a small almond-shaped structure found deep within the brain. It plays a crucial role in regulating emotions, fear responses, and the storage of memories, particularly those associated with negative or traumatic experiences. The amygdala's diverse structure consists of five major functional groups: basolateral nuclei, cortical-like nuclei, central nuclei, other amygdaloid nuclei, and extended amygdala [Neuroanatomy Amygdala, StatPearls]. The amygdala is connected to other parts of the brain involved in emotional regulation, such as the prefrontal cortex and the hypothalamus, allowing it to coordinate its activity with other areas. Damage to the amygdala has been linked to several mental health disorders, including post-traumatic stress disorder (PTSD) and depression [tsvetkov2015]. Understanding the anatomy of the amygdala can help medical professionals better diagnose, treat, and care for patients with these conditions.

Prior studies have shown associations between abnormalities of the amygdala and irritability. Irritability is associated with several psychiatric disorders, including ADHD. Suk et al took an additional step, exploring the associations of irritability with activation of the amygdala, and the associations of facial expression processing with activation of the amygdala. They recruited 59 children with disruptive mood and behavior disorder aged 10-18 with a self-reported Affective Reactivity Index (ARI) of at least 4. Major findings include increased activation in several regions of the brain in response to positive and negative facial expressions (happiness and fear). The regions of the brain were the right amygdala, right precuneus, right cingulate gyrus, bilateral cerebellum, right superior frontal gyrus, right middle occipital gyrus, and middle temporal gyrus. [[suk2023.pdf]]

The study aimed to examine the relationship between irritability in ADHD-Combined Presentation and altered functional connectivity. Functional connectivity was measured using Resting-state fMRI of the amygdala and nucleus accumbens in ADHD patients aged 12-23. Irritability was positively correlated with atypical functional connectivity. The amygdala had greater connectivity with the right inferior frontal gyrus and caudate/putamen, and less functional connectivity with the precuneus. The nucleus accumbens showed a positive correlation bewteen irritability and greater functional connectivity with the left posterior middle temporal gyrus and precuneus. [[mukherjee2022]]

***Basal Ganglia***

The basal ganglia consist of several, adjacent structures deep to the cerebrum. These structures are the striatum, subthalamic nucleus, and substantia nigra. The striatum contains the caudate, nucleus accumbens, olfactory tubercle, and lenticular nuclei. The lenticular nuclei are the putamen, globus pallidus externus, and globus pallidus internus [Neuroanatomy Basal Ganglia, StatPearls].

Tang et al investigated the association between basal ganglia morphology and motor response control. ADHD children aged 8-12 were evaluated via go/no-go tasks and shape-based morphometric analyses of T1-weighted 3D MPRAGE images using a 3T scanner. The results showed decreased volumes and inward deformation of the putamen and dorsal globus pallidus in male, ADHD children relative to male controls. The same findings were absent in female, ADHD children relative to female controls. There was also a positive correlation between decreased volume/inward deformation of these structures and poorer motor response control. [[tang2019.pdf]]

Shvarzman et al used diffusion tensor imaging (DTI) to investigate levels of iron deposition in the basal ganglia and their association with ADHD. They recruited ADHD children aged 8-12 for DTI of their brains, and also utilized brain-behavior analyses. They found that ADHD children had reduced iron in the bilateral limbic striatum. Lower tissue-iron levels in the bilateral limbic striatum correlated with anxious, depressive, and affective symptom severity. [[shvarzman2022.pdf]]

Cascone et al used MRI and fMRI to assess intrinsic dopamine availability in the basal ganglia and thalamus of ADHD children aged 8-12. The ADHD-only participants also underwent a crossover methylphenidate challenge. They found that increased iron in the putamen was negatively associated with successful response inhibition regardless of ADHD-status. During their crossover challenge, they also found that higher putamen and caudate iron levels positively correlated with better response to methylphenidate. This was seen in the ADHD children's improved task performance with methylphenidate. [[cascone2023.pdf]]

***Caudate***

The caudate nucleus is a crucial subcortical structure in the brain, located in the striatum of the basal ganglia, lateral to the thalamus. It consists of three parts - the anterior head, body, and tail, which work together with the putamen to contribute to cognitive, emotional, and learning processes. The caudate head is connected to the lateral and medial prefrontal cortices and manages memory acquisition, storage, retrieval, and manipulation. The caudate body and tail modulate learning acquisition. Their neurons primarily consist of GABAergic medium spiny neurons that inhibit other basal ganglia structures. [Neuroanatomy Caudate, StatPearls]

Greven et al conducted a cross-sectional study with the goal of detecting associations with brain structure volume with ADHD. They used brain MRI data from the Dutch NeuroIMAGE sample dataset of ADHD children and adult patients, unaffected siblings, and typically developing control individuals. They were measuring volumes of the whole brain, along with the caudate nucleus, putamen, nucleus accumbens, amygdala, globus pallidus, hippocampus, thalamus, and brainstem. The findings in ADHD patients consisted of a 2.5% decrease in total brain volume of ADHD patients, 3% decrease in total gray matter volume. Unaffected siblings had increased total brain volume relative to ADHD patients, but still decreased total brain volume relative to typically developing controls. Age appeared to be negatively associated with caudate and putamen volumes in typically developing controls. However, in ADHD patients and their unaffected siblings, age had no statistically significant association with caudate/putamen volumes. [[greven2015.pdf]]

Dang et al aimed to clarify the relationship between caudate asymmetry and ADHD symptoms. T1-weighted MRI scans of adults aged 18-35 were analyzed for caudate asymmetry. The ADHD score from the Test of Variables of Attention (TOVA) was used to assess attentional problems, while impulsivity, was measured using the Barratt Impulsiveness Scale, a self-report measure. The findings suggest that larger right relative to left caudate volumes correlate with higher attentional impulsiveness and worse ADHD scores on the TOVA. [[dang2016.pdf]]

Yang et al examined the dorsal caudate's functional connectivity with other parts of the brain in children with ADHD, using resting-state functional connectivity data from MRI scans. The results showed the dorsal caudate's positive connectivity with prefrontal areas, cingulate cortex, and temporal lobe, as well as its negative connectivity with precuneus, occipital cortices, and cerebellum. A correlation between the left dorsal caudate's connection to the left inferior frontal gyrus and severity of ADHD was also found. [[yang2017.pdf]]

The study aimed to clarify the relationship between subcortical regions and ADHD. Whole-brain voxel-wise resting state functional connectivity (rsFC) was measured via fMRI of ADHD children aged 7 to 18. Total ADHD, Hyperactivity and Inattention scores were collected using the Conners’ Parent Rating Scale Revised, Long Version, in order to evaluate associations between rsFC changes and ADHD. Structures of focus were the caudate, amygdala, putamen, pallidum and hippocampus. The study found that the caudate nucleus showed increased rsFC with the anterior cingulate and right insula. They also found that the increased rsFC of the caudate nucleus positively correlated with ADHD symptomatology. [[damiani2020.pdf]]

The study aimed to understand how changes in glutamate and GABA levels in the caudate nucleus and nucleus accumbens occur during attention control tasks. ADHD adults aged 31-51 years old were recruited for MPRAGE T1-weighted imaging and MRS scans while performing attention control tasks. During these tasks, smaller increases in glutamate and GABA were seen in ADHD patients compared to those without ADHD. These smaller increases also were found to positively correlate with worsening performance in the attention control tasks for ADHD patients. [[mamiya2022.pdf]]

***Cerebellum***

The cerebellum is an integral part of the human brain involved in vital motor function and balance control. It is in the posterior cranial fossa, posterior to the fourth ventricle. This area can be damaged in humans leading to a loss of controlled muscles movements, difficulty with balance and learning new motor skills. [Neuroanatomy Cerebellum, StatPearls].

This study aimed to investigate the relationship between ADHD and cerebellar/balance deficits. The study included ADHD children aged 7-11 that were using the Phyaction Balance Board, and evaluated with an international ataxia rating scale and Conners’ Continuous Performance Test. The results showed that ADHD patients' balancing task performance and sway amplitudes were poorer than the control group. [[goetz2017.pdf]]

This study aimed to understand the neural mechanisms of emotional dysregulation (ED) in children with ADHD and MDD. Participants included 22 ADHD and 21 MDD patients, all with clinical ED. These patients underwent resting-state functional connectivity analysis, voxel-based morphometry, and diffusion tensor imaging analysis, along with clinical rating scales for ED, ADHD, and MDD. The results showed increased rsFC in the cerebellum and supramarginal gyrus, decreased rsFC in the right supplementary motor area and right lateral parietal area, lower gray matter (GM) volume in the SMG, and both RSFC and GM were correlated with clinical rating scale scores for all patients with ED due to ADHD or MDD. [[wu2022.pdf]]

***Cingulate Gyrus***

The cingulate gyrus and cortex reside within the medial surface of the cerebral hemisphere and are part of the limbic system, playing a crucial role in numerous vital neural circuits which interact with structures such as the reward area of the limbic cortex. The set of Brodmann areas 24, 25, 31, 32, 33, 23, 26, 29, and 30 constitute the cingulate gyrus. This information is important for understanding the anatomy of the brain's limbic system, which plays a critical role in regulating emotions, motivation, and cognitive function. [[wadekane2022]] and [[StatPearls]]

The study aimed to investigate glutamate levels in the anterior cingulate cortex (ACC) and dorsolateral prefrontal cortex (DLPFC) of adults with ADHD and healthy controls using single-voxel proton MRS on a 3T scanner. Results showed increased ACC glutamate levels in ADHD patients, and a positive correlation between glutamate levels in the ACC and severity of hyperactivity/impulsivity symptoms in ADHD patients. [[bauer2016.pdf]]

The current study utilized voxel-based morphometry with DARTEL to measure regional gray matter volumes. The Culture Fair Intelligence Test and the d2-test were used to assess selective attention performance. Together these were analyzed to find correlations between gray matter abnormalities and ADHD symptoms. The researchers found that subjects with ADHD exhibited reduced GM volume in the anterior cingulate cortex (ACC), occipital cortex, bilateral hippocampus/amygdala, and widespread regions of the cerebellum in ADHD patients. GM volume in the ACC was negatively associated with test scores of selective inattention. [[bonath2016.pdf]]

The aim of this study was to investigate the association between dopamine transporter gene (DAT1) 3´UTR genotype and the cingulate cortical thickness in ADHD patients. Using brain MRIs from 46 ADHD patients homozygous for the 10-repeat allele and 52 ADHD patients with either 0 or 1 copies of the allele, researchers found that the homozygous individuals had increased thickness in the right cingulate gyrus and right Brodmann Area 24. [[fernandez-jaen2016.pdf]]

This study aimed to examine the subgenual anterior cingulate cortex (sgACC) of children diagnosed with ADHD-combined type (ADHD-C). The ADHD-C patients underwent Diffusion tensor imaging (DTI), resting-state functional MRI (rs-fMRI), and parent-based, clinical DSM-IV scoring of ADHD symptoms. They found a disconnected functional network between the sgACC, and the occipital lobe and cerebellum. Results also showed disrupted white matter in the subgenual cingulum bundle (sgCB), increased variability of spontaneous brain activity in the sgACC, and higher radial diffusivity in the sgCB. From their analyses, they found a negative correlation between increased clincal scores with sgACC spontaneous brain activity. [[zhan2017.pdf]]

The study examined dynamic regional cerebral blood flow alterations of ADHD children using event-related Arterial spin labeling (ASL) scanning. 17 healthy controls and 20 children with ADHD were scanned on a 3 Tesla MRI scanner during a go/no-go task. The right anterior cingulate cortex, frontopolar cortex, and orbitofrontal cortex (Brodmann Areas 32, 10, 11) activation was increased in ADHD children during the attention task. The findings suggest that ADHD children over-activated these regions to compensate for the increased attention demands. [[baytunca2021.pdf]]

***Corpus Callosum***

The corpus callosum is a crucial white matter structure in the brain that connects the left and right hemispheres to facilitate communication between them. Anatomically, it is divided into four parts: rostrum, genu, body, and splenium. It consists of approximately 200 million heavily myelinated nerve fibers. The corpus callosum is pivotal in integrating and transferring sensory, motor, and high-level cognitive signals between the two hemispheres. [[Statpearls]]

This study investigated whether there is a link between ADHD symptoms in adults over 60 years old and the thickness of their corpus callosum. Results indicated that in males the thickness of anterior third, anterior/posterior midbody, isthmus, and splenium of the corpus callosum was negatively correlated with inattention and hyperactivity. Females exhibited a positive correlation between the thickness of the rostral body of the corpus callosum and hyperactivity. [[luders2016.pdf]]

This study explored the changes in the white matter of the corpus callosum and their association with ADHD symptoms. In a case-control study conducted at Menoufia University Hospitals, researchers recruited ADHD children aged 3-14. Both behavioral and cognitive functions were evaluated by studying brain Diffusion Tensor Imaging (DTI) in correlation with radiological data from both groups. The results showed that the isthmus of the corpus callosum had a mean FA value lower in the ADHD group, indicating reduced white matter consistency. [[el-hadad2021.pdf]]

This review discusses that decreased growth rates in the premotor, motor, sensory, and parietal regions of the corpus callosum of ADHD patients. Children with decreased rostral corpus callosum volume were found to have increased impulsivity and hyperactivity. [[dupont2023.pdf]]

***Globus Pallidus***

The globus pallidus (GP) is located subcortical and medial to the putamen. It is named after its paleness due to relatively increased myelin, contrasting with the darker appearance of the neighboring structures. The basal ganglia encapsulate and split the GP, into globus pallidus externus (GPe) and globus pallidus internus (GPi). GPe is the lateral subdivision, while GPe is the medial one. It works in tandem with the caudate nucleus and putamen. Inhibitory input (GABAergic) is taken from several structures, including the substantia nigra and ventral pallidum. The GP is heavily involved in controlling conscious and proprioceptive movements, with GPe acting as a relay for information, while GPi outputs to the thalamus. [[StatPearls, maybe find Dupont or Agaolikum]]

In this study, the researchers aimed to investigate associations between functional brain connectivity profiles and sex differences in ADHD adults. Participants underwent structural MRI and rsfMRI on a 3 T full body MR scanner and seed-based connectivity analysis of the external globus pallidus (GPe) was performed. Their results showed that male ADHD patients had decreased functional connectivity compared to female ADHD patients, specifically between GPe and left middle temporal gyrus and middle frontal gyrus. They also found that ADHD males with comorbid depression showed decreased GPe FC with the occipital cortex. [[dupont2022.pdf]]

***Hippocampus***

The hippocampus is a key component of the brain that plays a vital role in memory consolidation, decision-making, and other cognitive functions. It is located within the inferior temporal horn of the lateral ventricle. Memory consolidation is a core function of the hippocampus, which is the process of generating long-term memory from short-term memory, which ensures that important information is stored for future use. Its neural circuits enable the storage and retrieval of information related to place, direction, and distance, allowing us to navigate our surroundings efficiently. Furthermore, it integrates various sensory inputs and interacts with other brain regions to regulate emotional responses and control social behaviors. [[Statpearls]]

The study aimed to compare amygdala and hippocampus volumes using MRIs of ADHD adults and controls. Clinician-administered diagnostic interviews and self-report scales were also collected. Results showed that there was no significant difference in volume of either region. However, they found hyperactivity in specifically ADHD patients negatively correlated with left amygdala volumes. [[nickel2017.pdf]]

***Hypothalamus***

The hypothalamic nuclei are split into the periventricular, medial, and lateral zones, surrounding the mammillary bodies and the third ventricle. It is connected to the cerebral cortex through the medial forebrain bundle, hippocampus through the fornix, amygdala through the stria terminalis, thalamus through the mammillothalamic tract, pituitary through the median eminence, and retina through the retinohypothalamic tract. Through a multitude of direct connections and interplay between the different anatomical areas in this motor hierarchy, the hypothalamus serves as the integrator and modulator of this network, ultimately allowing it to respond adaptively to both internal and external cues in order to maintain homeostasis. [[StatPearls]]

The association between the hypothalamus–pituitary–adrenal (HPA) axis and ADHD in non-stress states. Participants were male children with ADHD aged 6 to 14. ADHD was delineated into three sub-groups: ADHD-predominantly inattention type (ADHD-I), ADHD-predominantly hyperactive impulsive type (ADHD-HI), and ADHD-combined type (ADHD-C). The levels of cortisol and adrenocorticotropin hormone (ACTH) were evaluated per morning (8:00 am). ADHD patients overall showed decreased cortisol relative to the control group. The ADHD-HI group specifically showed even further decreased cortisol relative to the other two groups (ADHD-I and ADHD-C). No associations regarding ACTH were found. [[ma2011.pdf]]

***Middle Frontal Gyrus***

The middle frontal gyrus (MFG), part of the prefrontal cortex, plays an essential role in human cognitive function, facilitating attention, working memory, and language processing. It is located lateral to the superior frontal gyrus and medial to the inferior frontal gyrus. Various functional magnetic resonance imaging (fMRI) studies have shown that this region is actively involved in alerting, orienting, and reorienting of visuospatial attention. [[briggs2021]]

This study explores the middle frontal gyrus levels of major metabolites in children diagnosed with attention deficit hyperactivity disorder (ADHD). The results indicate decreased metabolite levels, including Cr (creatine and phosphocreatine), in ADHD subjects particularly in the right cerebral hemisphere. Cr was positively correlated with performance on attention tests and decreases in this metabolite may be associated with either ADHD or pharmacological treatment of these individuals with methylphenidate. [[tafazoli2013]]

***Nucleus Accumbens***

The nucleus accumbens (NAc) is a crucial part of the basal ganglia, located in the ventral portion of the striatum. It receives direct input from various brain regions such as the amygdala, hippocampus, thalamus, and prefrontal cortex through excitatory glutamatergic projections. Additionally, it also receives indirect dopaminergic inputs from the substantia nigra pars compacta. The NAc is a key component in modulating emotional responses, reward processing, and motor function. [[yan2022]]

***Pituitary***

The Pituitary Gland plays a crucial role in maintaining various vital functions in the human body, including cognitive functioning and attention. It is located inside the sella turcica of the sphenoid bone and is divided into the anterior lobe and posterior lobe. The pituitary gland produces hormones that regulate various physiological processes, such as growth, metabolism, reproduction, and sleep cycles. It also regulates the release of adrenocortical hormones such as cortisol which modulates the response to stress. [[Statpearls, fairchild2010]]

This study aimed to investigate if the different ADHD subtypes of inattentive (ADHD-I) and combined (ADHD-C) showed distinct cortisol reactivity responses to a psychosocial stressor compared with typically developing children. Participants studied include 52 children with ADHD-C, 23 children with ADHD-I, and 25 healthy control subjects. Stress was measured by comparing cortisol responses after a public speaking task. ADHD-I showed higher cortisol responsivity, while those with ADHD-C displayed blunted cortisol responses. Hyperactivity symptoms were linked to lower cortisol responsivity to stress in children with ADHD-I, but not ADHD-C. These findings suggest that low cortisol responsivity to stress might be a neurobiological marker for ADHD-C. [[west2009]]

The review aimed to understand if hyperactive/impulsive or combined type attention-deficit hyperactivity disorder (ADHD) has reduced basal cortisol secretion or cortisol hyporeactivity. Children with ADHD and comorbid oppositional defiant disorder demonstrated decreased basal cortisol and a decreased cortisol awakening responsivity. However, some studies reporting normal cortisol responses and others showing blunted cortisol responses in non-comorbid ADHD. [[fairchild2010]]

The study aimed to investigate the relationship between four functional polymorphisms in NR3C1 (encoding glucocorticoid receptor) and two in NR3C2 (encoding mineralocorticoid receptor), with childhood ADHD. Treatment response assessed in a 2-week, double-blind, placebo-controlled trial with methylphenidate. A specific haplotype of NR3C1 was associated with behaviors related to ADHD, comorbidity with oppositional defiant disorder, and executive function domains. Methylphenidate treatment was positively correlated with improvement on task-oriented behavior. [[fortier2012]]

***Putamen***

The putamen, located in the basal ganglia's dorsal portion, works in a complex cortico-basal ganglia network. It is responsible for integrating distinct functional channels and directing coordinated actions, adjusted according to external and internal stimuli. The putamen and globus pallidus make up the lentiform nucleus. It also combines with the caudate nucleus to form the striatum, which is part of the basal ganglia. Its roles include modulating learning, motor control, speech articulation, reward cognitive processes and addiction. [[StatPearls]]

The study aimed to examine the association between focal stroke lesions in children and ADHD/ADHD traits. Participants underwent psychiatric assessments including the Schedule for Affective Disorders and Schizophrenia for School-Age Children, Present and Lifetime Version (K-SADS-PL) and brain MRIs. Of the patients with ADHD/ADHD traits, the densest area of overlapping lesions was in the posterior ventral putamen. Of the remaining patients (no ADHD/ADHD traits), none of them had lesions in the posterior ventral putamen. They found that those with lesions in this region were more likely to have ADHD. [[max2002.pdf]]

The aim of this study is to investigate differences in putamen volumes among ADHD combined subtype male children with psychopathic traits and controls. Using past MRI scans, the putamens in both groups are analyzed but no local volume differences were found. However, a reversal of symmetry in the putamen is discovered in which children with ADHD tend to have smaller left relative to right putamens compared to their control counterparts who have smaller right relative to left putamens. [[wellington2006.pdf]]

The study aimed to explore differences in putamen functional connectivity between medication-naïve ADHD children and typically developing children. Using seed-based correlation analyses in resting-state fMRI data, it was found in the controls (TD children) that there was positive putamen functional connectivity with the bilateral sensorimotor areas, prefrontal cortex, insula, superior temporal gyrus, and subcortical regions. Negative putamen functional connectivity was observed in the bilateral parietal and occipital cortices. Negative putamen FC was also seen in the frontal and middle temporal cortices and cerebellum. ADHD children relative to controls had, increased left putamen FC with the right globus pallidus/thalamus, decreased left putamen positive FC with the right frontal and limbic regions, decreased left putamen negative FC with the right cerebellum and right temporal lobe, and decreased right putamen negative FC with the left cerebellum and right precuneus. [[cao2009.pdf]]

In this study, researchers investigated a specific genetic variant, rs945270 (reported to affect putamen volume), linked with increased symptoms of attention-deficit/hyperactivity disorder (ADHD) in 14-year-old adolescents. They used a large sample size of 1834 children and analyzed ADHD symptoms via their Strengths and Difficulties Questionnaire (SDQ). They also analyzed the Region-of-interest (ROI) analyses of putamen activation by functional magnetic resonance imaging (fMRI) using the Stop Signal (SST, for assessing response inhibition) and monetary incentive delay (MID, for assessing reward sensitivity) tasks. They found that the C-allele at rs945270 was negatively correlated with symptom scores, especially hyperactivity. However, in males, the c-allele was negative correlated with putamen activity during successful response inhibition, regardless of ADHD symptoms. In females, the c-allele was positive correlated with bilateral (right more than left) putamen activity during reward anticipation. Right putamen activation negatively correlated with ADHD symptoms. [[xu2017.pdf]]

***Striatum***

The striatum is a subcortical structure within the basal ganglia, consisting primarily of GABAergic projection neurons (SPNs) that receive glutamatergic inputs from various regions of the cerebral cortex, thalamus, and limbic system. Cortico-/thalamo-striatal projections carry these signals, and these signals are essential for controlling motor, procedural, and reinforcement-based behaviors in mammals. [[valjent2020]]

The study aimed to evaluate the association of localized dopamine increases and long-term clinical response to treatment with stimulant medications like methylphenidate in patients diagnosed with ADHD. Using positron emission tomography and [11C] raclopride, researchers found that dopamine increases in the ventral striatum were associated with reductions in symptoms of inattention during long-term methylphenidate treatment. The study also showed that increased dopamine in the temporal and prefrontal cortices led to improved ADHD symptoms. [[volkow2012]]

The study aimed to investigate the association between polygenic risk for childhood attention deficit/hyperactivity disorder (ADHD) and problematic alcohol use in young adulthood via dysfunction in the ventral striatum, which supports appetitive behaviors and reinforcement learning. The methods involved gathering genomic, neuroimaging, and self-report data from 404 Duke Neurogenetics Study participants, allowing calculation of polygenic risk scores for childhood ADHD based on a GWAS meta-analysis by the Psychiatric Genomics Consortium. This score was tested for associations with reward-related ventral striatum activity and self-reported problematic alcohol use. A mediational model was then used to test if ventral striatum activity links polygenic risk for ADHD to problematic alcohol use. The results found that polygenic ADHD risk was indirectly correlated with problematic alcohol use through increased ventral striatum activity. [[carey2017]]

This study aimed to examine changes in performance and fMRI activity during the anticipation of reward in children with ADHD symptoms, regardless of a primary diagnosis of ADHD. A total of 108 boys, aged 8–12 years were involved. This included 33 typically developing children and 75 boys who displayed symptoms of ADHD. Of those displaying symptoms 38 had a diagnosis of adhd and 37 had a diagnosis of ASD. They used event-related fMRI to assess performance and ventral striatum activation during reward anticipation. The results showed that children with ADHD symptoms, regardless of diagnosis, had reduced ventral striatum activity during reward anticipation. There was a positive relationship between parent-rated sensitivity to reward and greater anticipatory ventral striatum activity in children with ADHD symptoms. [[hulst2017]]

This study aimed to explore differences in dorsal striatum functional connectivity (FC) between men and women with attention deficit hyperactivity disorder (ADHD). The researchers used resting state fMRI data of adult participants curated from the Human Connectome Project. They performed seed-based correlations for caudate and lentiform nucleus (LN) FC and examined associations between ADHD symptom severity, inattention, and hyperactivity and specific patterns of dorsal striatum connectivity. Men showed significantly higher ADHD total score than women. In men, inattention was negatively correlated with LN FC with the right superior frontal gyrus. In women, inattention was negatively correlated with caudate FC with the right inferior parietal gyrus and positively correlated with LN FC with the left inferior frontal gyrus. Also in women, hyperactivity was positively associated with LN FC with a cluster in the dorsal anterior cingulate cortex and supplementary motor area. [[chen2021]]

***Substantia Nigra***

The substantia nigra (SN) is an essential part of the midbrain, playing a crucial role in regulating motor control and reward functions through its involvement in the basal ganglia. The SN consists of two regions, pars compacta (SNpc) and pars reticulata (SNpr). The SNpc contains dopaminergic neurons while the SNpr has gamma-aminobutyric acid-containing (GABAergic) neurons. SN projections to the putamen, known as the nigrostriatal pathway, are closely linked to Parkinsonian motor deficits. SN dopaminergic neural projections travel through the medial forebrain bundle and form connections with other regions of the brain, affecting a wide range of functions including cognitive, emotional, and motor control. [[Statpearls]]

The study aimed to investigate the maturation of dopaminergic (DA) pathways from over time and explore any differences in healthy children, children with ADHD, and young adults. The researchers used functional connectivity MRI (rsfMRI) to examine changes in connectivity patterns between the ventral tegmental area (VTA) and substantia nigra (SN) in relation to age. They found that functional connectivity matures significantly over time and varies by age group. Age-related increases of the VTA FC with limbic regions, default mode network, NAc, and insula. Age-related increases of the SN FC in thalamus but decreases of the SN FC with motor and medial temporal cortices were also observed. ADHD children had greater VTA FC in amygdala, left parahippocampus, right globus pallidus, left thalamus, and right insula, and greater SN FC in amygdala and insula than TDC. ADHD children had stronger VTA FC in thalamus, subthalamic nucleus, globus pallidus and stronger SN FC in left amygdala and insula than TDC. In ADHD children, age-related VTA FC increases in superior frontal/precentral gyri, ACC, inferior OFC, and insula, and age-related SN FC decreases in precentral gyrus, paracentral lobe, and lingual gyrus. [[tomasi2014]]

The cross-sectional, analytical study measured size and echogenicity of the substantia nigra using TCS to determine an association between these and ADHD. Participants included 34 ADHD and 34 healthy individuals aged 6–12 years. Results showed increased SN hyper-echogenicity and decreased thalamic nuclei hypo-echogenicity in ADHD children. Typically developing children with a family history of ADHD showed similar results for ADHD children. [[sepehrmanesh2023]]

***Tegmentum***

The Ventral Tegmental Area (VTA) is a part of the brainstem that plays a crucial role in regulating dopamine levels, which are essential for maintaining attention and focus. The VTA is also interacts with the mesolimbic reward circuitry and the prefrontal cortex. This area is composed of a series of circuits which can be involved in motor learning as well as reward-seeking behavior. [[trutti2019]] The ventral tegmental area (VTA) has become the focus of a major research area in recent years due to its involvement in the mechanism of attention deficit hyperactivity disorder (ADHD). This area, located in the midbrain, is involved in regulating activity among prefrontal cortex and ventral striatum regions. Research has shown that dysfunctions in dopamine and noradrenaline pathways are implicated in causing the symptoms of ADHD, such as inattention, hyperactivity, and impulsivity. [[aydin2019]]

Try to find more

***Thalamus***

The thalamus is a central structure of the diencephalon composed of mostly gray matter. It connects with the contralateral thalamus through the interthalamic adhesion. It is bounded laterally by the internal capsule and anterolaterally by the caudate head. Each thalamic side can be divided into three groups: lateral, medial, and anterior nuclei. These are split by the internal medullary lamina. In addition to anatomic grouping, these nuclei can also be categorized based on function. There are three categories: Relay (lateral nuclear group, medial nuclear group, and anterior nuclear group), Reticular, and Intralaminar nuclei. Relay nuclei projections target specific cortical areas and the nuclei have been split into lateral nuclear group (ventral posterolateral, ventral posteromedial, and lateral geniculate nuclei), medial nuclear group (medial and pars paramediana) and anterior nuclear group. [[Statpearls thalamus & nuclei, check for accuracy]]

The study aimed to examine the neurobiological basis of inattentiveness in ADHD by analyzing functional MRI data from children and young adolescents with the disorder. The objective was to investigate cortico-pulvinar functional pathways during sustained attention and their association symptoms of inattentiveness. The method used to conduct the study involved analyzing visual attention task-based fMRI data from 22 ADHD children and 22 controls. Results indicated that subjects with ADHD exhibited reduced pulvinar activations bilaterally, decreased bilateral pulvinar FC with the right prefrontal regions, and increased right pulvinar FC with the bilateral occipital regions. Additionally, the left pulvinar activation magnitude had a negative correlation with the DSM-IV inattentive index for the ADHD group. [[li2012]]

This cross-sectional analysis investigated neuroanatomical alterations related to ADHD diagnosis and subtype, focusing on subjects without comorbidity. 121 children with uncomorbid ADHD (54 iADHD and 67 cADHD) were analyzed using T1-weighted structural MRI images from the ADHD-200 database. Regional GM increase of the right thalamus and precentral gyrus was found to be linked only to the inattentive subtype. The right thalamus volume positively correlated with inattentive severity in iADHD [[fu2021]]

***Physiology***

***Dopamine***

Dopamine is a chemical messenger or neurotransmitter in the brain that plays an essential role in regulating functions such as motivation, cognitive function, and motor control. In ADHD, there is believed to be a deficiency of dopamine transmission due to several factors: genetic predisposition, environmental exposure, and/or prenatal developmental issues. This theory explains the efﬁcacy of methylphenidate (MPH) and dextroamphetamine in treating ADHD symptoms because they help normalize dopamine levels, thereby reducing hyperactivity and improving attention span. The role of dopamine in ADHD is supported by various lines of evidence, including the efﬁcacy of psychostimulant drugs, genetic predisposition, environmental factors, and the recent increase in research investigating the involvement of dopamine receptors. [[taken from all dopamine, come back]]

DRD1, or the Dopamine Receptor D1 gene, has been implicated in the pathophysiology of Attention-Deficit Hyperactivity Disorder (ADHD). Recent studies on individuals diagnosed with ADHD have found an initial association between this genetic variation and symptoms of hyperactivity and attention deficits. This correlation may lead to future research and development of targeted treatment options for ADHD, focusing on the specific role of DRD1 in patients experiencing these symptoms. [[taken from all dopamine, come back]]. The study aimed to evaluate the contribution of DRD1, DRD2, DRD3, DRD4, DRD5, DAT1, TH, DBH and COMT to attention-deficit hyperactivity disorder (ADHD). They conducted a case-control study of genotyped 533 ADHD patients and 533 sex-matched unrelated controls. Four DRD1 SNPs were correlated with ADHD in children (rs835616, rs835541, rs863126 and rs265977). A two-marker haplotype (rs863126–rs265977) was specifically associated with childhood combined-type ADHD. The latter finding was replicated in an independent sample of German families with combined-type ADHD children. [[ribases2012]]. This study aimed to investigate the roles of dopamine D1 receptors (D1Rs) and microglial activation in attention-deficit/hyperactivity disorder (ADHD), using positron emission tomography (PET). Twenty-four ADHD individuals underwent PET measurements for D1Rs and activated microglia. The ADHD group showed reduced anterior cingulate cortex (ACC) D1R, while increased microglial activation was found in the dorsolateral prefrontal cortex (DLPFC) and orbitofrontal cortex (OFC). This reduction in D1R correlated with severity of hyperactivity in ADHD individuals, while increased microglial activation correlated with processing speed/attentional deficits specifically in the ADHD group. [[yokokura2020]].

The DRD2 gene, which encodes the dopamine receptor D2, has been extensively studied in relation to attention deficit hyperactivity disorder (ADHD). Researchers have identified several polymorphisms within this gene and conducted several meta-analyses examining their associations with ADHD. [[drd2, safavi2022]] The study investigated the association between Taq1A polymorphism and ADHD in children. DRD2-Taq1A gene polymorphism was genotyped in 50 ADHD patients and 50 controls. Phenotype distributions of A1 allele were positively correlated with ADHD, as did the heterozygous A1A2 genotype. In addition, ADHD cases showed lower distribution of the homozygous A2A2 genotype. [[moro2019]] The study aimed to examine changes in two specific polymorphisms, rs2283265 and rs27072, within the dopamine receptor D2 (DRD2) and dopamine transporter gene (SLC6A3), respectively, in ADHD patients. The methods employed involved a descriptive-analytical study with 100 ADHD patients and 100 controls to analyze rs2283265 and rs27072 polymorphisms using PCR-RFLP method and restriction enzymes. They found a significant correlation between the distribution of these polymorphisms and ADHD. [[safavi2022]].

DRD3, also known as the Dopamine receptor 3 gene, plays a significant role in the etiology of ADHD (attention deficit hyperactivity disorder) symptomatology. The overall role of DRD3 in ADHD (Attention-Deficit/Hyperactivity Disorder) appears to be related to its the Catechol-O-Methyltransferase (COMT) gene. [[fageera2020]]. The study aimed to investigate the role of candidate genes, such as DRD3 (Ser-9-Gly), in ADHD using a comprehensive approach. This included combining dimensional behavioural analysis with pharmaco-dynamic evaluation and association/linkage testing. The researchers evaluated children with ADHD at baseline observation followed by methylphenidate administration or placebo, each for one week. They assessed various quantitative behavioural and cognitive dimensions. By combining family-based (FBAT) and quantitative trait genetic analyses with nuclear families, they found the T allele was associated with poorer teacher-rated behavioral scores during the MPH week in boys. The results provide convergent evidence for DRD3 (Ser-9-Gly)'s role in ADHD and its modulation of behavior, including response to pharmacological probes. [[fageera2018]]. The study aimed to examine the joint effect of two functional variants in DRD3 and COMT on ADHD behaviors. Methods included assessing 362 children with ADHD by parents and teachers during a baseline evaluation, followed by one week each of MPH and placebo administered in a double-blind crossover design. Results showed statistically significant association between DRD3 and COMT genotypes and Conners’-Teachers scores. COMT Met/Met genotype had lower scores without MPH, suggesting that stratifying children according to their COMT genotypes helped detect statistically significant effects of DRD3 genotype. [[fageera2020 fix this]]

DRD4 plays a complex and noteworthy role in the development and diagnosis of attention-deficit hyperactivity disorder (ADHD) in children. This study aimed to investigate the link between organophosphate pesticides (OPs), attention-deficit/hyperactivity disorder (ADHD) in children, and their association with oxidative stress and genetic polymorphisms. The research involved 93 children diagnosed with ADHD and 112 control children from North Taiwan. They collected the serum samples of both groups to analyze six dialkyl phosphate (DAP) metabolites of OPs and oxidative stress biomarkers. Additionally, they identified the genotype variations of dopamine receptor D4 gene (DRD4) in the children with ADHD. The results revealed that children with ADHD had significantly higher dimethylphosphate (DMP) levels than control children. Furthermore, those carrying DRD4 GA/AA genotypes were less likely to have ADHD compared to DRD4 GG carriers. The estimated value of the AP (the influence of gene-environment interaction on ADHD risk) was found to be 0.59, which indicated that nearly 60% of ADHD cases in DMP-exposed children with the DRD4 GG genotype were attributed to this. The study showed that DRD4 GG children who had been exposed to high DMP and had high HNE-MA levels had an increased risk of developing ADHD. [[chang2018]]. This study aimed to explore the association between dopamine receptor D4 (DRD4) methylation and phthalate exposure on continuous performance test (CPT) variables in children with Attention-Deficit Hyperactivity Disorder (ADHD). The researchers analyzed urine samples to assess mono-(2-ethyl-5-hydroxyhexyl) phthalate (MEHHP), mono-(2-ethyl-5-oxohexyl) phthalate (MEOHP), and mono-n-butyl phthalate (MBP) levels. They also examined the methylation status of CpG sites in DRD4. The results showed a significant interaction effect between CpG26 and CpG28 methylation combined with the MEHHP level when assessing omission errors. [[kim2018]]. The study aimed to investigate the interaction of regulating dopamine D4 receptor (DRD4) on functional brain activity during resting state in ADHD children by measuring regional homogeneity (ReHo) and functional connectivity (FC). Resting-state fMRI data was analyzed from 49 children with ADHD. DRD4 2R allele carriers had decreased ReHo in the bilateral posterior cerebellar lobes, but increased ReHo in the left angular gyrus. The study also found that DRD4 2R allele carriers showed decreased FC of multiple brain structures towards the left angular gyrus. These structures were the left striatum, right inferior frontal gyrus, and cerebellar lobes. Additionally, it was found that some structures had increased FC, such as the left superior frontal gyrus, medial frontal gyrus, and rectus gyrus. [[qian2018]].

Norepinephrine

Serotonin

***Genetics***