Science, Education and Innovations in the Context of Modern Problems
Issue 11, Vol. 8, 2025

TITLE OF THE RESEARCH ARTICLE

Neuropsychological and Neurofeedback-Based Management of Attention Deficit Hyperactivity Disorder (ADHD): A Cognitive-Behavioral and Neuroelectrical Approach

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Issue web link https://imcra-az.org/archive/385-science-education-and-innovations-in-the-context-of-modern-problems-issue-11-vol-8-2025.html

Keywords Attention Deficit Hyperactivity Disorder (ADHD); Neurofeedback (NFB); Neuropsychological Rehabilitation; Cognitive-Behavioral Therapy (CBT); Neuroelectrical Regulation; Self-Regulation; Fronto-Cortical Dysfunction.

Abstract

The neuropsychological management of Attention Deficit Hyperactivity Disorder (ADHD) has undergone a significant transformation in recent decades through the integration of technological innovations in neuroscience. This paper explores the theoretical and clinical underpinnings of Neurofeedback (NFB) as an emerging neuropsychological intervention for ADHD with or without hyperactivity. Neurofeedback, derived from biofeedback and operant conditioning principles, enables individuals to observe and modulate their cortical activity in real time, fostering self-regulation of neuroelectrical processes associated with attention, impulsivity, and motor control. Drawing upon a synthesis of empirical studies, neuroimaging findings, and cognitive-behavioral models, this research demonstrates that ADHD symptoms are rooted in dysfunctional neural oscillations, particularly within fronto-cortical and fronto-striatal circuits. The paper emphasizes how NFB protocols—such as theta/beta training, slow cortical potential (SCP) regulation, and sensorimotor rhythm (SMR) modulation—contribute to improved attentional control, inhibition, and executive function. This study also situates NFB within the broader neurodevelopmental rehabilitation framework, proposing its integration with cognitive-behavioral therapy (CBT) and educational neuropsychology for a holistic, multi-level intervention. The findings highlight the potential of NFB to enhance adaptive functioning and neuroplasticity while reducing dependence on pharmacological treatment.

Citation. Ouahiba D; Iatidel A. (2025). Neuropsychological and Neurofeedback-Based Management of Attention Deficit Hyperactivity Disorder (ADHD): A Cognitive-Behavioral and Neuroelectrical Approach. *Science, Education and Innovations in the Context of Modern Problems*, 8(11), 1340–1354. https://doi.org/10.56334/sei/8.11.14

Received: 03.03.2025 | Accepted: 20.08.2025 | Publishing time: 01.11.2025

Introduction:

New technological techniques are not only part of our daily lives but have also become essential tools and devices in the health sector. In the field of neuropsychological rehabilitation, modern technological advancements have contributed to the development of several electronic devices and programs that assist in the accurate and effective assessment of various neuropsychological diseases and disorders. Among these techniques, we mention the Neurofeedback technique.

Neurofeedback emerged in 1972 during the development of Electroencephalography (EEG), which is a medical device that records the brain's electrical activity using electrodes placed on the scalp.

Neurofeedback is considered a type of Biofeedback technique (Hengameh Marzbani, Hamid Reza Marateb, Marjan Mansourian, 2016: 143), which is a broader field encompassing a set of techniques that analyze a biological signal to train a specific function in the body.

The objective of this technique is to train the individual to control the activity of specific brain areas by using a signal derived from their neural activity. Thus, it is a method that allows the individual conscious control over brain activity. It includes different, organized stages in a closed-loop system: receiving the neural activity signal, processing and describing the neural signal in real-time, and representing the neural signal (Charles VERDONK, 2023: 129).

Numerous studies have demonstrated its effectiveness as a therapeutic program for improving mental health and the management of various neuropsychological disorders, among which we mention Attention Deficit Hyperactivity Disorder (ADHD).

ADHD is characterized by three core symptoms: inattention deficits, impulsivity, and motor hyperactivity. Scientists attribute these disorders to several factors, the most important of which are neurological factors. Recent studies relying on modern medical imaging techniques (anatomical and functional) have demonstrated a neural model suggesting that the attention deficit is specifically due to a deficit in inhibition, primarily located at the fronto-cortical level.

Moreover, studies using tasks such as go/no-go, stop-signal, Stroop, or flanker have proven a deficit in activation during the performance of these tasks in the frontal cortex areas, specifically the dorsolateral prefrontal cortex, the ventrolateral prefrontal cortex, and notably, the anterior cingulate cortex (ACC) in its dorsal part. Studies in cases of hyperactivity have also shown a significant decrease in the activity of cingulate regions during digital Stroop tasks. This supports the meta-analysis, which shows using functional imaging that the activity of the anterior cingulate region is significantly reduced in cases of hyperactivity and attention deficit.

In this paper, we will attempt to demonstrate the role of Neurofeedback technology in the management of Attention Deficit Hyperactivity Disorder (ADHD).

Problem Statement:

The nervous system is made up of many billions of neurons that constantly transmit information to one another. Brain cells use electricity to communicate; this electric current is called a brain wave (Onde Cerebrale) and represents manifestations of brain activity. These waves enable the execution of various human mental functions.

Thus, neural activity consists of synaptic excitation of the dendrites of various pyramidal neurons in the cerebral cortex located within the skull. The amplitude of the signal varies depending on the degree of synchronization of the activity of different cells beneath the skull (i.e., according to the number of cells excited at the same time).

Therefore, the brain can generate very slow frequencies, valued at 0.05 Hz, and fast frequencies reaching up to 500 Hz. These recorded frequencies have been classified into frequency bands, with each band designated by a Greek letter.

Obtaining these frequencies doesn't tell us *what* the individual is thinking, but it does inform us *that* they are thinking (Mark F. Bear, Barry W. Connors, Michael A. Paradiso. 2016: 659). Consequently, these frequencies are linked to specific behaviors such as attention levels, sleep, wakefulness, and even disordered states like epilepsy or loss of consciousness. Among these disorders is Attention Deficit Hyperactivity Disorder (ADHD) with or without hyperactivity. Current research indicates that children with this disorder show somewhat stable differences in Electroencephalogram (EEG) results concerning brain electrical activity when compared to typical children, especially regarding Theta (θ) activity in the frontal and central regions, which is associated with drowsiness and low arousal (Chabot & Serfontein, 1996; Clarke, Barry, McCarthy, & Selikowitz, 1998, 2001; El-Sayed, Larsson, Persson & Rydelius, 2002; Lazzaro et al., 1998 cited in Sandra K. Loo, Ph.D, 2003, P2).

In the largest EEG study on ADHD to date (with over 400 children with ADHD), Chabot and Serfontein (1996) found that children with ADHD exhibited an increase in Theta activity, slight increases in frontal Alpha activity, and generalized decreases in the mean Beta frequency. The EEG results showed that the technique accurately identified 94.8% of normal children and 93.1% of children with ADHD (Chabot, Merkin, Wood, Davenport, & Serfontein, 1996 cited in Sandra K. Loo, Ph.D, 2003: 2). Monastra and colleagues (1999; 2001) reached the same results. It should be noted that this study used a single electrode on the top of the head (Cz), whereas many other EEG studies have used a large number of electrodes (9-32) distributed across various brain regions. All showed an increase in slow-wave activity in the brain wave patterns of children with ADHD, indicating reduced cortical activity in response to task demands. Some studies relying on EEG also recorded a stable decrease in the Beta band (which indicates increased cortical arousal) and Alpha activity, while other groups recorded a decrease in Beta activity in the frontal and central regions (Chabot & Serfontein, 1996; Clarke et al., 1998, 2001; Lazzaro et al., 1998; Mann, Lubar, Zimmerman, Miller, & Muenchen, 1992) contradicting other groups (Janzen, Graap, Stephanson, Marshall, & Fitzsimmons, 1995; Kuperman, Johnson, Arndt, Lindgren, & Wolraich, 1996; Satterfield, Schell, Backs, & Hidaka. 1984). The reason may be due to methodological differences, such as variations in study samples (pooled versus clinical samples), diagnostic procedures, the EEG data collection equipment, and procedures. Some scientists also attributed it to the recorded differences in EEG activity patterns according to the DSM-IV ADHD subtypes (Inattentive, Hyperactive-Impulsive, or Combined). Studies on the recorded differences between the subtypes of this disorder showed that children with the Combined Type (CT) of ADHD exhibit stable and relative activity in the Theta band, as well as higher Theta/Alpha and Theta/Beta ratios compared to those with the Inattentive Type (I) (Clarke et al., 1998, 2001). In contrast, children with the Inattentive-I type showed more relative Alpha levels in the posterior regions than those with the Combined-CT type. This explains the slower cognitive processing and increased rates of daydreaming among these children. From this perspective, how can the Neurofeedback technique contribute to reducing the manifestations of the disorder in this group of children?

The Nature of Attention Deficit Hyperactivity Disorder:

It is not a disease but a syndrome, a nosological entity (Entité Nosologique) that includes a set of simultaneous symptoms: inattention and behavioral disorders of the type hyperactivity and impulsivity (P. Berquin, 2005). It is a neurodevelopmental disorder (Francis Eustache, Sylvane Faure, Béatrice Desgranges, 2013).

According to DSM-5, this disorder is classified under Neurodevelopmental Disorders—defined in the same classification as a group of conditions that manifest during development. These disorders typically appear during the early developmental stages, usually before the child enters primary school. They are characterized by a developmental deficit that leads to functional impairment at the personal, social, academic, or occupational level. The form of the developmental deficit varies from specific limitations in learning or Executive Function control to neurodevelopmental disorders of social skills or intelligence. These disorders often appear interconnected (DSM-5, 5th edition, 2015: 33). It is a persistent pattern of inattention and/or hyperactivity-impulsivity that interferes with functioning or development, characterized by (1) and/or (2):

1- Inattention: Persistent pattern of six (or more) of the following symptoms for at least six months, to a degree that is inconsistent with the developmental level and that negatively and directly impacts social and academic/occupational activities:

- Often fails to give close attention to details or makes careless mistakes in schoolwork, work, or other activities.

- Often has difficulty sustaining attention in tasks or play activities (e.g., has difficulty remaining focused during lectures, conversations, or lengthy reading).

- Often does not seem to listen when spoken to directly (e.g., seems elsewhere, even in the absence of obvious distraction).

- Often does not follow through on instructions and fails to complete schoolwork, chores, or duties in the workplace (e.g., starts tasks but quickly loses focus and is easily sidetracked).

- Often have difficulty organizing tasks and activities (e.g., difficulty managing sequential tasks, difficulty keeping materials and belongings in order, messy, disorganized work, poor time management, failing to meet deadlines).

- Often avoids, dislikes, or is reluctant to engage in tasks that require sustained mental effort (e.g., schoolwork or homework; for adolescents and adults: preparing reports, filling out forms, reviewing lengthy articles).

- Often loses things necessary for tasks or activities (e.g., school materials, pencils, books, tools, wallets, keys, paperwork, eyeglasses, mobile phones).

- Is often easily distracted by external stimuli (for adolescents and adults, may include unrelated thoughts).

- Is often forgetful in daily activities (e.g., doing chores or errands, for adolescents and adults: returning calls, paying bills, keeping appointments).

2- Hyperactivity and Impulsivity: Persistent pattern of six (or more) of the following symptoms for at least six months, to a degree that is inconsistent with the developmental level and that negatively and directly impacts social and academic/occupational activities:

- Often fidgets with or taps hands or feet, or squirms in seat.

- Often leaves seat in situations when remaining seated is expected (e.g., leaves their place in the classroom, office, or other workplace, or in other situations that require remaining in place).

- Often runs about or climbs in situations where it is inappropriate (Note: In adolescents or adults, this may be limited to feeling restless).

- Often unable to play or engage in leisure activities quietly.

- Is often "on the go," acting as if "driven by a motor" (e.g., is unable to be or is uncomfortable being still for prolonged time, as in restaurants, meetings; may be experienced by others as being restless or difficult to keep up with).

- Often talks excessively.

- Often blurts out an answer before a question has been completed (e.g., completes other people's sentences; cannot wait for turn in conversation).

- Often has difficulty waiting his or her turn (e.g., while waiting in line).

- Often interrupts or intrudes on others (e.g., butts into conversations or games or activities; may start using other people's things without asking or receiving permission; for adolescents and adults, may intrude into or take over what others are doing).

Furthermore:

- Several inattentive or hyperactive-impulsive symptoms are present before age 12 years.

- Several inattentive or hyperactive-impulsive symptoms are present in two or more settings (e.g., at home, school, or work; with friends or relatives; in other activities).

- There is clear evidence that the symptoms interfere with, or reduce the quality of, social, academic, or occupational functioning (DSM-5, 5th edition, 2015: 68-69).

Neuro-Anatomical and Functional Approach to Attention in the Normal State:

There are several types of attention: Vigilance, Sustained Attention, Divided Attention, and Selective Attention. The latter involves the activation of the Anterior Cingulate Cortex (ACC) and also includes a distributed neural circuit, comprising the frontal cortex (oculomotor areas), cingulate, and posterior parietal regions, in addition to subcortical thalamic and striatal connections. These regions are also activated during simple tasks involving sustained attention or shifting attention. The cortical areas of this circuit form a fronto-parietal loop that is independently excited during visuomotor and visuospatial orientation tasks or working memory during visuospatial tasks. A relative dissociation has been observed between the Anterior Cingulate Cortex (ACC) and the Dorsolateral Prefrontal Cortex (DLPFC), where DLPFC activation was recorded in the absence of ACC activation during tasks involving information processing within working memory. Conversely, the ACC is activated when tasks require divided attention, a novel response, or the maintenance of a correct response. MacDonald et al. hypothesized that the DLPFC is involved in the representation and maintenance of voluntary attention to a task, while the ACC is involved in evaluative processes such as error monitoring or the presence of conflict or interference in responses that occurs during the conflict between two contradictory responses. The ability to primarily inhibit learned behavior is impaired upon damage to the Ventro-orbital side of the prefrontal region. Functional imaging has confirmed that the orbital region is activated during the extinction of a behavior that has become inappropriate. In fact, a distributed circuit seems necessary for this type of behavioral inhibition. It also includes the Inferior and Middle Frontal Gyri, especially within the Right Lobe.

Therefore, normal executive functions such as sustained attention and behavioral inhibition depend on the inferior and middle frontal (e.g., cingulate cortex) and/or basal (orbital lobe) regions. Complex processes such as conflict processing, errors, and emotions lead to the activation of a network of frontal regions, including the cingulate cortex, supplementary motor area (SMA), orbitofrontal cortex (OFC), ventrolateral prefrontal cortex (VLPFC), and parts of the central gray nuclei and the thalamus. There is a significant correlation between the density of the right Anterior Cingulate Cortex and the ability to perform tasks requiring attentional control in children aged 5 to 16 years. There is substantial evidence that the orbital cortex develops in children at 4 years of age (V. Emond, C. Joyal, H. Poissant, 2008: 108-109).

Among the models for the neural systems of attention (Michel Habib, 2018), the Posner team's model is highlighted as the most relied upon in recent studies. It posits that the neural networks of attention consist of three systems: an anterior system called the "Executive" system, a posterior system called the "Orienting" system, and an arousal system also called the "Alerting" system. The role of each system was determined using several methods: first, clinical study on cases of neurological damage; second, experimental studies on animals; and finally, based on the results of functional neuroimaging on normal living subjects (*In vivo*). The type of neurotransmitters involved in each system was identified based on pharmacological studies on both animals and humans.

It has been shown that the Dopaminergic anterior system allows for executive control and decision-making regarding voluntary behaviors, and the Cholinergic posterior system allows for selective attention orienting. Studies have also demonstrated the independence of these systems from each other, as well as the simultaneous excitation of heterogeneous neural regions specific to each of the three systems, which may overlap in some parts.

The Arousal or Alerting system is composed of several ascending noradrenergic pathways—a group of nerve fibers ascending from the locus coeruleus in the brainstem and distributed across multiple areas of the cerebral cortex, including the parietal and frontal regions. This system is predominantly located in the left hemisphere, responsible for phasic processes (meaning instantaneous and complex), whereas orienting processes are active (slow and extended over time) and are predominantly found in the right hemisphere.

Studies have distinguished between two types of orienting systems: the first is a dorsal system that includes the posterior parietal regions (the Intraparietal Sulcus or SIP) and a central frontal area involved in eye movement called the Frontal Eye Field (FEF). These two regions are involved in monitoring rapid strategy during attention. The second is a Ventral system consisting of the Temporo-parietal junction and the Ventral Frontal Cortex. In other words, the Dorsal system is involved in using external information to orient attention (thus, Top-Down—from cognition to the perceptual system), allowing for the voluntary orientation of attention towards the target region. This is called Endogenous Attention. In contrast, the Ventral system allows for the reorientation of attention toward an unexpected region, thus following a Bottom-Up pattern, which permits the release of attention from the current state to shift it toward a new one, thereby responding to the exogenous function of attention.

Numerous studies have shown the involvement of several frontal regions, specifically on the medial side of the two cerebral hemispheres: the Anterior Cingulate Gyrus (ACC) and the adjacent cortex, including the Supplementary Motor Area (SMA).

The lateral frontal regions are associated during the performance of various tasks that involve interference between conflicting information, such as the interference item in the Stoop test. Generally, the Anterior Cingulate Gyrus region is excited in all interference situations, whether sensory, verbal, spatial, or even social, or generally during error detection.

Studies have distinguished between two networks within the monitoring system: the first network includes the Anterior Cingulate Gyrus (ACC) and the Opercular region (including the Insula) and is involved in maintaining the level of attention throughout the task performance, allowing for task continuity. The second network includes lateral frontal and parietal cortical regions slightly different from those involved in orienting, but its role is different: monitoring and modifying performance in real-time during the task (Michel Habib, 2018).

Neuro-Anatomical and Functional Approach to Attention Deficit Hyperactivity Disorder:

Attention Deficit Hyperactivity Disorder (ADHD) is characterized by three core symptoms: inattention deficit, impulsivity, and motor hyperactivity. Scientists attribute these disorders to several factors, the most important of which are neurological factors. Recent studies relying on modern medical imaging techniques (anatomical and functional) have demonstrated a neural model suggesting that the attention deficit is primarily due to damage to the Attentional Network, represented by the Cingulo-Frontal-Parietal (CFP) loop that integrates the attentional system. This includes three interacting subsystems: Orienting, Detection, and Alerting/Vigilance. The structures specifically involved are the dorsal anterior Cingulate Cortex (daMCC), the Dorsolateral Prefrontal Cortex (DLPFC), the Ventrolateral Prefrontal Cortex (VLPFC), the Striatum, the premotor areas, and the Thalamus, as well as the Cerebellum, which intervenes in parallel with attentional and cognitive networks.

Newer hypotheses link inattention symptoms and executive deficit and hyperactivity-impulsivity symptoms with acute executive deficit, which represent the following brain circuits: the Fronto-Striato-Cerebellar Circuit (also called the simple executive loop), which specifically includes the Ventrolateral Prefrontal Cortex (VLPFC), the Dorsolateral Prefrontal Cortex (DLPFC), and the Fronto-Striatal, Fronto-Cerebellar, and Fronto-Parietal networks. This loop is involved in disorders of response inhibition, attention, working memory, organization, and planning, and is involved in all executive tasks such as the Stroop test and Go/No-Go. The Fronto-Limbic Circuit (also called the acute executive loop) is specifically represented by the Medial and Orbital Prefrontal Cortex (OMPFC), the Anterior Cingulate Gyrus, the Striatum, and the Ventro-Medial Fronto-Limbic (VMPFC) structures. The limbic circuits are associated with disorders of emotional control, motivation, reward, hyperactivity, and impulsivity. Recent studies on neural activity during rest also provide new information about functions in the Resting State and vigilance that can lead to a disturbance of the attentional system in cases suffering from hyperactivity (Michel Bader, 2016: 199-200).

Fundamentally, this disorder is described as damage at the level of the Fronto-Striatal Loop. The development of brain imaging techniques, particularly anatomical and functional Magnetic Resonance Imaging (MRI), has allowed for the identification of affected areas in ADHD cases:

- Disruption in the volume (density) of gray matter in various brain regions.

- Structural disruption in white matter involved in higher cognitive and emotional functions.

- Functional disruption with decreased activity in the left prefrontal cortex, anterior cingulate gyrus, right parietal lobe, occipital cortex, claustrum, and thalamus. However, some studies showed the opposite, finding excessive activity in the left prefrontal cortex, the left thalamus, and the right paracentral lobule (SIMAO DE SOUZA Clément, 2017: 25).

These disturbances persist into adulthood, with the exception of the caudate nucleus.

From a neurocognitive perspective, various neuropsychological theoretical approaches have emerged to explain the disorder, particularly the neurocognitive ones:

- Barkley's Model (1997): Focuses on Executive Functions and emphasizes the Executive Dysfunction Syndrome (*syndrome de dysfonction exécutive*). It is mainly represented by a disorder at the level of Behavioral Inhibition and Cognitive Self-Regulation (*L'autorégulation cognitive*) (SIMAO DE SOUZA Clément, 2017: 26). According to the developer of this model, the most impaired executive functions involve the process that allows the maintenance of a stable state of attention and the Shift (Switching) from one attentional level to another when required, ensuring the necessary flexibility to continue and execute the set goals. Studies have proven that children with ADHD find it difficult to perform tasks that require these functions, particularly those characterized by interference, which leads to a disorder in selective attention manifested primarily by a disorder in interfering response inhibition (represented in the Stroop test by the written word interfering with naming the color), a deficit in flexibility with a tendency to maintain the previous task or instruction (as in the Wisconsin test), and finally, a disorder at the level of working memory, which appears particularly as a weakness in the reverse digit span. Barkley summarizes the working memory disorder, the attention switching deficit, the inhibition deficit from one task to another, and planning (including Scheduling or programming another response, and Monitoring of current performance) into one term: Inhibition Deficit (*Déficit de l'inhibition*). Among the concepts mentioned by Barkley are two concepts: Self-Regulation (*L'autorégulation*) and Internalization of Language (*L'internalisation du langage*). According to this scholar, the inhibition process that develops in the child through maturation and experience allows for the acquisition of what he called Behavioral Syntax (*Syntaxe comportementale*), coordinated with the acquisition and development of language, especially "Internal Language," which appears in early childhood and is involved in the ability to regulate (*La capacité à réguler*) their own behaviors (Michel Habib, 2018).

The concept of Self-Regulation refers to the literature of developmental psychology and reflects the child's potential to regulate their own thoughts, emotions, and behaviors, with the necessity of another person's presence for this regulation to occur. From a neurological perspective, studies found that the anterior and medial part of the cingulate gyrus is involved in such situations. This region is linked to the sensory cortex on one hand and the limbic structures on the other, which explains its involvement in sensory-type tasks as well as those related to emotional tasks. Studies have demonstrated the importance of this ability, especially for the child's social integration, and its development is linked to the development of the attentional loops (Michel Habib, 2018).

- Delay Aversion Model (Le modèle de l'aversion au délai): Developed by Sonuga-Barke, who suggests not an inhibition deficit but a search for immediacy along with a motivational process (SIMAO DE SOUZA Clément, 2017: 26), meaning Delay Aversion. He suggests that hyperactivity is not a result of a deficit in behavioral inhibition but rather a "performing reaction to a latent emotional pattern" that makes them seek to avoid delay, which leads to hyperactivity, inattention, and impulsivity in these children. This deficit has been interpreted from a neurofunctional perspective, as the deficit is attributed to a disorder in the neurotransmitter secretion mechanism, particularly Dopamine, which is a subcortical mechanism. Studies on animals have shown that this neurotransmitter plays an important role in regulating goal-directed behaviors, making it the "Hormone of Motivation." Various neurochemical mechanisms involved in motivated behavior in animals and the various anatomical structures have been identified and grouped under the term "Reward System Circuit (*Circuit de la récompense*)," which is characterized by a complex set of nuclei and their interconnections that form the "Interface between Emotion and Action" (Michel Habib, 2018). The importance of this model was demonstrated through numerous studies based on functional imaging results, which found a functional disorder of the reward system in cases of ADHD (SIMAO DE SOUZA Clément, 2017: 26).

In a slightly different framework from that built by Sonuga-Barke and Castellanos, the Norwegian scholar T. Sagvolden suggests that Delay Aversion in children with ADHD is an indicator of a functional deficit in a system governed by the Dopaminergic mechanism and involved in the phenomena of reinforcement and extinction. According to this approach, a child suffering from this disorder needs immediate and frequent reinforcement to be able to complete their performance. This is achieved through what is called the "Delay Gradient (*Gradient de délai*)" curve. In normal cases, the longer the delay between the stimulus and the reward, the weaker the response. This is known as the "Reinforcement Delay Gradient." This type of gradient is rapid in children with ADHD, resulting in a steep (poor) curve, and the same response will be obtained even if a short delay time is recorded. This explains impulsivity, the important element in this model (Michel Habib, 2018).

During 2005-2006, Sonuga-Barke and Castellanos integrated the two previous models (SIMAO DE SOUZA Clément, 2017: 26). The feeling of Delay Aversion results from a functional disorder of the reward mechanisms (*Circuits méso-limbiques*) and also from the early peripheral characteristics of the condition, while the Inhibition Deficit results from a Meso-Cortical functional disorder. Therefore, Delay Aversion, Executive Functional Disorder, and poor task engagement result in inattention, hyperactivity, and impulsivity (Michel Habib, 2018).

From here, a distinction was made between "Cold" Executive Disorders, which represent an inhibition deficit with a functional disorder at the level of the Fronto-Striatal Loop located on the lateral side of the frontal cortex, and "Hot" Executive Disorders, which represent emotionally based decision-making, involving motivational processes and depending on the connections between the Orbito-Frontal Cortex and the Ventral Striatum (*cortex orbito-frontal et striatum ventral*) (SIMAO DE SOUZA Clément, 2017: 26).

The Nature of Neurofeedback

In the foundational work on Biofeedback in French, Rémon and Rémon stated: "An analysis of the basic principles of Biofeedback shows that the fundamental 'behavior' by which an individual can succeed—more or less quickly—in mastering a new skill or an unconscious biological phenomenon, can be the result of a process of 'conditioning' and 'reinforcement' of this behavior. This may require many attempts, i.e., learning that is not necessarily immediately easy." This passage demonstrates the basic premise of the Neurofeedback technique: based on the learning model.

This technique relies on the principles of Operant Conditioning from the Neuro-Behavioral Theory to treat neuroelectrical activity. Cases receive real-time feedback (at the moment of task performance) on their brain wave patterns, typically focusing on the Alpha, Beta, Delta, Theta, and Gamma bands.

The technical manifestations of Neurofeedback are as follows: The recorded biological signal is the neuroelectrical activity, or at least the simple part that can be recorded. This neural signal represents a mixture of activities with different frequencies and waves, and the signal can then be broken down into several physiological activities called "rhythms or frequencies." Each rhythm is associated with a specific behavioral state of arousal. There are many types of Neurofeedback protocols that focus on different rhythms depending on the neuropsychological objective.

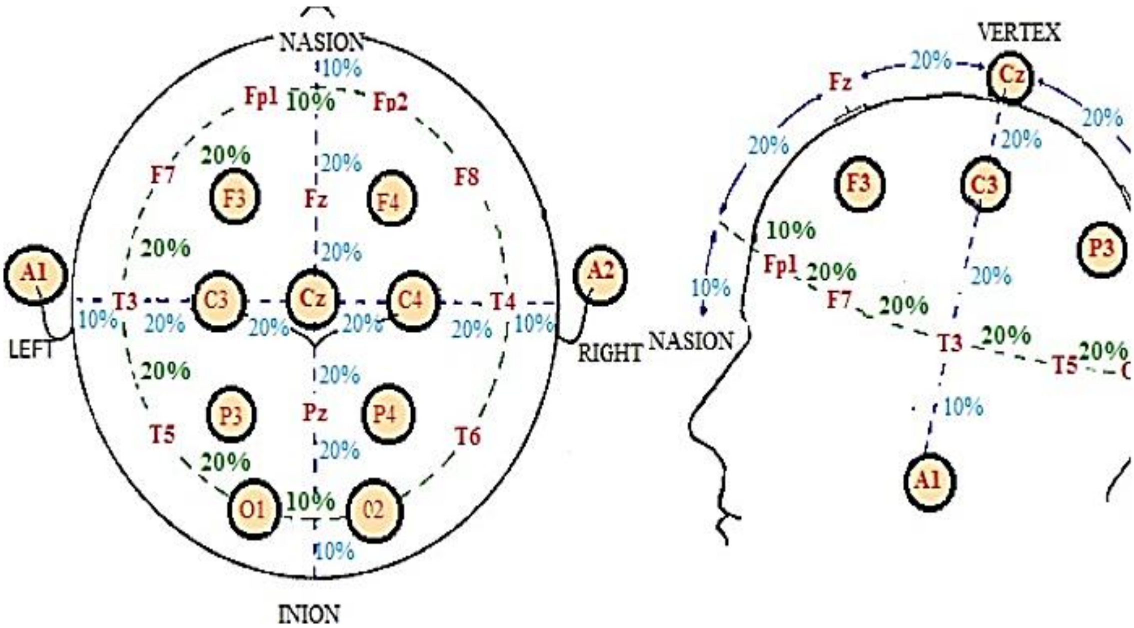
Therapeutic protocols based on Neurofeedback aim to improve cognitive functions by training specific Electroencephalographic frequency bands.

Brain Electrical Activity:

The activity of the exposed cortex in monkeys was recorded as early as 1875 (Dale Purves, George J Augustine, David Fitzpatrick, William Hall, Anthony-Samuel LaMantia, Léonard White, Translator: Jean-Marie Coquery, Nicolas Tajeddine, Philippe Gailly, 2012: 632). In the early 1950s, it became possible to record the activity of nerve cells by recording the Action Potential (PA) for a single cell by implanting very small electrodes inside the brain. These microelectrodes can be placed next to the cells (Extracellular Recordings) or inside the cells (Intracellular Recordings). Modern techniques for extracellular recording have made it possible to distinguish the activity of approximately 40 cells simultaneously (Bryan KOLB, Ian Q. WHISHAW, G. CAMPBELL TESKEY, translated by Marie-Hélène Canu, Erwan Dupont, Nicolas Narvaez Linares and Marion Noulhaine, 2019: 222). However, in 1929, the German scientist Hans Berger was the first to record human neural activity on the scalp (Dale Purves, George J Augustine, David Fitzpatrick, William Hall, Anthony-Samuel LaMantia, Léonard White, Translator: Jean-Marie Coquery, Nicolas Tajeddine, Philippe Gailly, 2012: 632), relying on the Electroencephalography (EEG) device. This device allows us to quickly detect what the brain is doing.

The neural activity of the brain, known as the Electroencephalogram (EEG), is obtained through the synchronized activity of pyramidal neurons, a specific type of cell in the brain. These cells represent 70% to 85% of the cells in the Neocortex layer and are considered excitatory cells that use the neurotransmitter Glutamate. These pyramidal cells are considered the output cells of the cerebral cortex and are therefore called Principal Cells. This type of cell can also be identified by a distinct electrophysiological characteristic, as they typically emit a long-term Action Potential (PA) (which may exceed a millisecond) (Alexandre Lacroix, 2014: 24-25). The activity of these cells reflects the results obtained in the EEG in the regions defined by the electrodes placed on the scalp. Several patterns of electrical activity, known as brain waves, can be distinguished by their amplitude and frequency. Frequency refers to the speed at which the waves oscillate, measured by the number of waves per second (Hz), while amplitude refers to the strength of these waves, measured in microvolts (mu V).

A set of electrodes is distributed in specific areas on the scalp. Generally, there are 19 electrodes distributed over the entire head in positions corresponding to the underlying cortical brain regions (Dale Purves, George J Augustine, David Fitzpatrick, William Hall, Anthony-Samuel LaMantia, Léonard White, Translator: Jean-Marie Coquery, Nicolas Tajeddine, Philippe Gailly, 2012: 633). Some specify 21 electrodes, where 19 electrodes are used to record cortical regions and two others as reference electrodes (Hengameh Marzbani, Hamid Reza Marateb, Marjan Mansourian, 2016: 145). The first letter of the electrode position indicates its location (F=Frontal, P=Parietal, T=Temporal, O=Occipital, C= Central), while the numbers are associated with the cerebral hemisphere: the number 1 represents the Left Hemisphere, while the number 2 represents the Right Hemisphere. The letter Z indicates that the position extends along the central midline, extending from the forehead to the back (i.e., the posterior region). FP1 and FP2 correspond to the left and right frontal poles, respectively. The letters A1 and A2 represent the right and left regions of the earlobe (mastoid/auricular), which are the positions for the reference electrodes.



Marzbani, H., Marateb, H. R., & Mansourian, M. 2016 :145

The recordings obtained through each pair of electrodes show a slight differentiation, attributed to the fact that each pair represents a sample of the activity of a group of cells belonging to different brain regions. Four electrical phenomena were arbitrarily identified (Dale Purves, George J Augustine, David Fitzpatrick, William Hall, Anthony-Samuel LaMantia, Léonard White, Translator: Jean-Marie Coquery, Nicolas Tajeddine, Philippe Gailly, 2012: 633). We have:

- Delta (δ) waves: Slow frequencies, less than 4 Hz and typically of large amplitude, reflecting deep sleep.

- Theta (τ) waves: Frequencies ranging from 4 to 7 Hz, which can be recorded during both sleep and wakefulness.

- Alpha(α) waves: Located between 8 and 13 Hz and appear mainly in the occipital areas of the cerebral cortex, associated with states of rest during wakefulness (Mark F. Bear, Barry W. Connors, Michael A. Paradiso, 2016: 655).

- Mu (μ) waves: Frequencies similar to Alpha waves but with significant amplitudes in the motor and somatosensory areas.

- Gamma (γ) waves: Among the rapid frequencies, ranging between 30 and up to 90 Hz, appearing during cortical arousal or sustained attention (Mark F. Bear, Barry W. Connors, Michael A. Paradiso, 2016: 657).

Table 1: Summary of Key Brainwave Frequencies and Their General Characteristics:

Type of Brainwave Frequency	Frequency Range (Hz)	General Characteristics
Delta	1-4	Sleep, healing, complex problem solving, unconsciousness, deep

		loss of consciousness.
Theta	4-8	Creativity, insight, deep states, unconsciousness, ideal meditative state, depression, anxiety, distraction/inattention.
Alpha(α)	8-13	Wakefulness and calm, readiness, meditation, deep relaxation.
Low Alpha(α)	8-10	Recall/Retrieval.
High Alpha(α)	10-13	Improved cognitive performance.
Sensorimotor Rhythm (SMR)	13-15	Mental alertness, physical relaxation.
Beta	15-20	Thinking, concentration, sustained attention, tension, alertness, arousal.
High Beta	20-32	Intensity, hypervigilance, anxiety.
Gamma	32-100 or 40	Learning, cognitive processing, problem-solving tasks, brain activity, brain regulation.

(Hengameh Marzbani, Hamid Reza Marateb, Marjan Mansourian, 2015: 144)

Functional Aspects of the Excited Brain Areas:

Neuronal activity possesses rich information about its neural functions. When cells are excited, they generate electrical impulses. The brain's electrical activity, obtained by the Electroencephalography (EEG) device, can be recorded by placing electrodes around the skull.

Neurologists observed that lesions occurring in specific brain areas produce distinct symptoms mostly related to those regions. For instance, the Frontal Lobe areas FP1, FP2, FPZ, F3, F4, F7 are responsible for immediate and sustained attention, time management, social skills, emotions, affects, as well as working memory, executive planning, moral thinking, and personality. Each area reflects a specific task or feeling. Proper identification of these regions allows for the provision of the best and most accurate treatment using Neurofeedback.

The Parietal Areas Pz, P3, and P4 process what is conceptually programmed in the frontal areas. The Left Parietal Lobe recognizes complex grammatical rules, naming objects, sentence construction, and mathematical processes, while the Right Parietal Lobe recognizes directional maps, spatial recognition, and recognizing the difference between left and right.

The Temporal Areas T3, T4, T5, and T6 have many functions. The left regions are linked to various reading functions (recognizing written words), memory, learning, and positive thinking, while the right side is linked to music, anger, face recognition, and the sense of direction.

Visual memories, skilled reading (i.e., the practiced reader), and traumatic memories, especially those related to visual memories, are processed in the Occipital Lobes O2, O1. These lobes also assist in locating objects in space, seeing colors, and recognizing drawings, specifically object recognition, reading, writing, and spelling.

The areas in the Sensorimotor Cortex Cz, C3, C4 are concerned with the conscious and voluntary control of all skeletal movements, such as typing, playing musical instruments, handwriting, operating complex machines, speaking, and the ability to identify the source of bodily sensations.

Neurologists also mentioned that the Motor Cortex assists the cerebral cortex in coding physical and cognitive tasks. Therefore, individuals suffering from a disorder in perceiving the logical sequence of cognitive tasks can benefit from the Neurofeedback technique along the motor cortex in the left hemisphere C3. Training along the sensorimotor areas in the right lobe may stimulate emotions, feelings, and calmness. The areas along the sensorimotor cortex are usually trained in cases of epilepsy to reduce manifestations of sensorimotor response.

Sensorimotor area training can also treat stroke, epilepsy, paralysis, ADHD, and sensory/motor integration disorders.

Generally, electrodes are placed to obtain an EEG for one side of the brain. For example, Low Beta and Beta are trained on the right C4 and left C3 sides of the brain, respectively. If the positions on the two sides of the brain are reversed, undesirable results will be obtained. For example, training the Low Beta wave on the left side will lead to a reduction in mental energy instead of improving concentration. Therefore, the positioning of EEG electrodes during the application of Neurofeedback is very crucial.

Stages of the Neurofeedback Technique:

The Neurofeedback technique consists of different stages organized into a loop:

1. Collection of the Neural Activity Signal (*Recueil du signal de l'activité cérébrale*): Neural activity is measured by collecting the electrical activity signal generated by a group of neurons spread throughout the brain, using an Electroencephalography (EEG) device placed on the scalp or inside the skull, or via a blood oxygen level-dependent signal in brain blood vessels using functional Magnetic Resonance Imaging (fMRI).

2. Real-Time Processing and Characterization of the Neural Signal (*Traitement et caractérisation du signal cérébral en temps réel*): Neural activity must be processed using quantitative standard tools for analysis. Analyzing the neural activity allows for the determination of its temporal characteristics (e.g., signal amplitude) or its effect (signal strength) using the descriptor device.

3. Representation of the Neural Signal (*Représentation du signal cérébral*): The signal obtained by the descriptor device is displayed to the client in a visual (e.g., bar graph) or auditory (sound) format. This information helps the client know the level of their activity in specific neural areas targeted by Neurofeedback. This enables them to determine the strategy they will adopt (e.g., recalling pleasant memories, thinking of certain music, etc.) to control the activity of that specific area in their brain (Charles VERDONK, 2023: 129).

Neurofeedback Technique Approaches:

There are two main methods for applying this technique:

1. Slow Cortical Potential (SCP) Neurofeedback: This method is applied to brain skills for the self-regulation of arousal and relaxation states. The subject must train skills to prepare the brain for mental or motor tasks. This method has shown positive effects on concentration and attention, and can reduce impulsive behavior and lead to a state of calm. Thus, it is applied to cases of ADHD, addiction, sleep disorders, eating disorders, and epilepsy.

2. Frequency Band Neurofeedback: This includes the basic frequency bands: SMR (Sensorimotor Rhythm), Theta, and Beta Neurofeedback. This technique is also used for cases of ADHD, sleep disorders, etc.

Furthermore, there are two modes used in rehabilitation relying on the Neurofeedback technique: monopolar and bipolar.

- The monopolar mode involves placing the active electrode in a specific location on the skull. The signal derived from this electrode is recorded and then compared to a second electrode called the reference electrode. The brain activity value at the active electrode is obtained by subtracting the reference electrode activity from the active electrode activity.

- In contrast, the bipolar mode involves placing two active electrodes in separate locations on the skull. The difference between the signals recorded by these two electrodes is the fundamental principle of the Neurofeedback.

Neurofeedback and Attention Deficit Hyperactivity Disorder (ADHD):

The Neurofeedback technique involves recording neural activity associated with specific symptoms, displaying it directly and clearly to the client, and asking them to perform a corrective activity. Although a modern technique, this practice is not new. About ten years after Hans Berger discovered EEG recording in 1935, the first experiments with the Neurofeedback technique were recorded. This technique has been adopted as an adjunctive therapeutic procedure to other treatments in the clinical field for ADHD. Studies have shown that individuals with this disorder have increased Theta frequencies above average, especially in the frontal (anterior) part of the brain during the day, which causes distraction and lack of focus on tasks, and also leads to motivational problems and may result in daydreaming.

Studies have also found that people with ADHD suffer from dysregulation in Beta frequencies, which are too slow, causing them problems in information processing and the sustained attention process.

To manage this disorder, the subject is asked to sit in front of a screen where a simplified representation of their targeted neural activity is displayed. The therapist is in front of a second screen, viewing the EEG recording and able to change the exercise difficulty level by adjusting the spectral power thresholds and time (Mathilde Meissirel, Gaëlle Mougin, Jean Vion-Dury, 2019: 03), depending on the adopted therapeutic protocol which is determined according to the rhythms to be modified.

There are seven types of Neurofeedback for the management and treatment of various disorders. Among the types used in the treatment of ADHD is Frequency/Power Neurofeedback. This is the most frequently used in the Neurofeedback field, relying on 2 to 4 electrodes, sometimes called "Surface Neurofeedback." It is used to change the amplitude or speed of a specific electrical wave in specific brain regions to treat ADHD, anger, and sleep disorders.

Slow Cortical Potential Neurofeedback (SCP-NF) improves the slow cortical activity direction to treat ADHD, epilepsy, and migraines.

Low-Energy Neurofeedback System (LENS) sends weak electromagnetic signals to change the client's brain waves while they are at rest with their eyes closed. This technique has been adopted to treat neurological injuries, ADHD, insomnia, fibromyalgia, restless legs syndrome, anxiety, depression, and anger.

Among the therapeutic protocols adopted for the management of ADHD is the Beta protocol. Beta activity is a good indicator of mental capabilities, and any dysregulation in this activity reflects mental and physical disorders such as depression and ADHD and sleep disorders. Beta brain waves are associated with the intensity of consciousness, strength of focus, and problem-solving ability, as drugs used to stimulate alertness and concentration, such as Ritalin and Adderall, also stimulate the brain's production of Beta waves.

The Beta protocol is used to improve concentration and attention by stimulating an increase in Beta in the 12-14 Hz range, improving reading skills by stimulating the 7-9 Hz range, and delivering positive changes in academic performance. It also improves sports performance, cognitive processes, reduces fears, overthinking, Obsessive-Compulsive Disorder (OCD), alcoholism, and insomnia by stimulating the 14-22 Hz and 12-15 Hz ranges. Simultaneously, this therapeutic protocol in Neurofeedback improves cognitive performance during sleep, in addition to reducing fatigue and stress (visual and auditory Beta stimulation). Beta waves in the 12-15 Hz (SMR) range reduce anxiety, epilepsy, anger, and stress.

Among the studies that relied on this technique is the study by Rasey, Lubar, McIntyre, Zoffuto, & Abbott (1995), where they increased the Beta band 16-22 Hz and decreased high Theta and low Alpha bands. Electrodes were fixed at the centro-parietal areas CPZ, PCZ over 20 sessions, and the study found an improvement in the attention skill of the study sample. In another study by Egner & Gruzelier (2001), they elevated Low Beta 12-15 Hz and 15-18 Hz and inhibited Theta 4-7 Hz and High Beta 22-30 Hz. The electrodes were fixed 12-15 Hz in the right central region C4 and 15-18 Hz in the left central region C3 for 10 sessions, and the results showed a significant increase in attention skill. These are the same results reached by Fuchs, Birbaumer, Lutzenberger, Gruzelier, & Kaiser (2003) by increasing Beta activity 15-18 Hz and SMR 12-15 Hz and inhibiting Theta activity at the C3, C4 areas for 36 sessions. The study by Heinrich, Gevensleben, & Strehl (2007) showed the treatment of epilepsy and ADHD by increasing Sensorimotor Rhythm (SMR) activity and inhibiting Theta activity at the central areas C4, Cz. ADHD was found to be treatable by reducing the degree of inattention, hyperactivity, and impulsivity by increasing Beta activity 16-20 Hz and inhibiting Theta at the Fcz, Cpz brain areas for 40 sessions (Lubar, Swartwood, Swartwood, & O'Donnell, 1995). The same results were reached by researchers by increasing Beta activity to 13-20 Hz and inhibiting Theta activity in the central areas Cz, C3 in a study by Heinrich, Gevensleben, & Strehl (2007).

In addition to the previous protocol, there is also the Theta protocol, which is also used in the treatment and management of ADHD, as well as the treatment of anger, depression, daydreaming, distractibility disorder, and emotional disorders. Theta waves are also associated with many brain functions such as memory, emotion, creativity, sleep, meditation, and hypnosis. These waves are also linked to the first stage of sleep when sleep is light and the person can easily wake up. Among the studies that demonstrated the importance of this protocol is the study by Perreau-Linck, Lessard, Lévesque, & Beauregard (2010) on a sample whose chronological age ranged from 8.13 years and underwent the therapeutic protocol of Theta and Sensorimotor Rhythm (SMR) at the central area Cz. The study concluded with an improvement in the symptoms of ADHD.

Furthermore, the "Beta/Theta" protocol focuses on the Beta rhythms associated with states of alertness, caution, and central attention, and the Theta rhythms representing a state of quiet wakefulness, drowsiness, and napping. This protocol aims to enhance cognitive strategies for maintaining alertness and attention by allowing the client to increase spectral power in the Beta range and decrease it in the Theta range. If these conditions are met, at a certain threshold and for a certain period, the client is informed via a visual and/or auditory signal (Mathilde Meissirel, Gaëlle Mougin, Jean Vion-Dury, 2019: 03). Among the studies that demonstrated the success of this protocol in the management of ADHD are Palsson et al. (2001), Orlandi (2004), Lévesque, Beauregard, & Mensour (2006b), Leins et al. (2007), and Gevensleben et al. (2009), which were applied to samples of cases aged between 8 and 13 years, with the application period ranging from 18 to 40 sessions. The electrode position was at the central area Cz in all studies. The researchers concluded with an improvement in the effects of the disorder, as well as an improvement in attention, concentration, memory, symptoms of hyperactivity, and distractibility, in addition to improved skills localized in the anterior cingulate cortex.

Conclusion:

The Neurofeedback technique contributes to the conscious control of brain waves using the Electroencephalography (EEG) device. During therapy relying on Neurofeedback, the extracted electrophysiological components of the EEG signal are displayed to the client in an auditory (sound), visual (video), or combined (audio and video) format. This technique aims to modify neural activity to change behavior, thus highlighting the therapeutic potentials for various neurological and psychological disorders. All studies have confirmed the effectiveness of this therapeutic technique in the management of ADHD symptoms. Currently, scientists are working on determining methods for processing signals derived from Neurofeedback by identifying precise neural areas to obtain functional and localized feedback results. The Neurofeedback process is important for a good and dynamic understanding of the brain, as well as for precise identification of the brain's functional activity and improving the connection between the brain and behavior.

Methodology

This study follows a qualitative and integrative research design based on systematic literature review and theoretical synthesis. Empirical data were drawn from peer-reviewed publications indexed in Scopus, PubMed, and PsycINFO between 2010 and 2024. Selection criteria included clinical and experimental studies addressing the application of neurofeedback in ADHD populations, particularly among children and adolescents. The analysis involved three main stages: (1) Theoretical Mapping: Review of foundational literature on neuropsychological and behavioral models of ADHD; (2) Comparative Protocol Analysis: Examination of major NFB paradigms—SMR, theta/beta ratio, and SCP training—in terms of mechanisms and clinical outcomes; and (3) Interpretive Synthesis: Integration of neurophysiological, psychological, and pedagogical perspectives to conceptualize NFB's role in ADHD rehabilitation. The methodological rigor was ensured through critical evaluation of sample sizes, EEG measures, outcome indices (attention, impulsivity, and executive performance), and longitudinal data consistency.

Ethical Considerations

This paper adheres to the ethical principles of research integrity and data protection outlined by the University Mohamed Lamine Debaghine–Setif 2. All secondary data used were obtained from publicly available and ethically approved studies. No personal or clinical participant data were collected directly by the authors. The ethical dimension of neurofeedback application is also discussed, particularly regarding informed consent, therapeutic transparency, and child participant safety in clinical trials.

Author Contributions

Both authors contributed equally to the conception, analysis, and writing of this paper.
- Ouahiba Djenoune: Conceptual framework, neuropsychological analysis, and literature review.
- Iatidel Aguida: Data synthesis, theoretical integration, and critical discussion of neurofeedback methodologies.
Both authors approved the final version of the manuscript and agree to its publication.

Acknowledgements

The authors would like to express their appreciation to the Unité de Recherche sur le Développement et la Réhabilitation Humaine (URDRH) at the University Mohamed Lamine Debaghine–Setif 2 for their academic support. Special thanks are extended to the neuropsychology research staff and students who provided constructive feedback on early drafts of this study.

Funding Statement

This study received no external funding. It was conducted as part of the ongoing academic research initiatives under the University Mohamed Lamine Debaghine–Setif 2.

Conflict of Interest

The authors declare that they have no conflict of interest regarding the authorship or publication of this article.

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