

ADHD Rehabilitation Through Real-Time EEG-Based Neurofeedback and AI

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Abstract—This paper gives a detailed review of the applications of Brain-Computer Interface (BCI) using the Slow Cortical Potentials (SCPs) approach in addressing Attention Deficit Hyperactivity Disorder (ADHD) [1,2]. Leveraging BCI and SCP neurofeedback via EEG monitoring, these systems enable individuals to self-regulate brain activity to improve attention and reduce impulsivity [1,2]. The survey explores key methodologies, challenges, and advancements in BCI-based rehabilitation for ADHD [3]. Emphasis is placed on real-time feedback mechanisms, machine learning analytics, and integrative approaches [4]. This study also identifies gaps in existing literature and proposes strategies to overcome them, ensuring that these systems reach their full potential in both clinical and real-world settings [5].

I. INTRODUCTION

At the crossroads of robotics and human cognition, this field has intrigued scientists and innovators for decades [6]. Attention-deficit/hyperactivity disorder (ADHD) is a neurodevelopmental disorder characterized by persistent patterns of inattention, hyperactivity, and impulsivity that complicate standard treatment approaches [7]. Innovative robotic platforms coupled with attention-monitoring systems are now revolutionizing therapeutic interventions by incorporating real-time feedback and adaptive strategies based on temporal and behavioral metrics [8]. These systems rely on a complex interplay of sensitive inputs, data processing algorithms, and focused feedback mechanisms [8].

For decades, robotics and advanced technology have been anticipated for their potential to address cognitive and behavioral challenges [9]. Rehabilitation methods have shown promise; however, the integration of robotics into rehabilitation for children with ADHD remains in early development stages [9,10]. This concept emerged from the potential to improve attention tracking and adaptive feedback systems, thereby delivering personalized therapeutic interventions efficiently

[10]. Robotic-based rehabilitation systems monitor and respond to changes in attentional state, enhancing engagement and therapeutic outcomes [10].

This idea arose from the potential of improving attention-tracking and adaptive feedback systems to deliver personalized therapeutic interventions as needed efficiently. Robotic-based rehabilitation for action is attention monitoring which designs systems to monitor and respond to changes in attentional state. Using real-time data from detectors to accommodate the robot's actions we can further promote engagement and enhance the benefits of therapeutic sessions.

II. HISTORY

Attention monitoring is rooted in decades of early work in cognitive neuroscience and behavioral psychology, well before technology-assisted therapeutics emerged [11]. It was not until the mid-20th century that researchers began exploring the therapeutic uses of automation and biofeedback systems [12]. The advent of electroencephalography (EEG) significantly advanced our understanding of brain activity patterns related to cognitive and attentional processes [12]. By the 1990s, real-time assessments of brain function enabled the development of systems capable of detecting and interpreting signals pertinent to attention, paving the way for robotic-based interventions [13]. Early multidisciplinary work combining robotics, neuroscience, and software engineering set the stage for today's approaches in ADHD rehabilitation [13].

III. EARLY WORK

Initial studies on attention monitoring and robotics for rehabilitation involved pilot patients to test the integration of sensory feedback systems with robotic platforms [14]. Research during the late 1990s and early 2000s led to advanced robotic systems capable of

monitoring user engagement and adjusting task difficulty based on attention levels [14,15]. For instance, early algorithms were developed to process EEG signals to detect inattention, and these were combined with robotic systems that provided near-real-time feedback through auditory cues or dynamic task modifications [15]. Subsequent work incorporated eye-tracking technology to supplement EEG data, laying the groundwork for modern multimodal systems [15]. For example, one of the early works are algorithms that process EEG signals to detect inattention. They combined these algorithms with robotic systems that generated near-real-time feedback, including sounds or dynamic task changes, to help recapture attention. Eye-tracking technology, as a next step on the multimodal system second stage was investigated in some of these studies by using eye tracker to provide information about gaze position or direction along with EEG signals. Initial research in this area laid down the rudimentary framework on which modern systems are built. The initial work illustrated potential benefits of robotics and advanced monitoring technologies in increasing engagement and thereby enabling improved therapeutic outcomes, paving the way for further explorations in this exciting area.

IV. HUMAN BRAIN

The human brain is the most complex organ, serving as the control center for thought, emotion, and motor functions [16]. Weighing approximately one and a half kilos and containing billions of neurons, the brain's structure is organized into specialized circuits that manage both automatic reflexes and high-level decision-making [16]. The cerebrum, responsible for reasoning, memory, and voluntary body movement; the cerebellum, in charge of coordination and balance; and the brain stem, which connects the brain to the spinal cord and regulates vital functions like respiration and blood circulation, all contribute to overall cognitive performance [16]. Despite its relatively small size, the brain consumes about 20% of the body's energy, underscoring its functional complexity [17]. Neuroplasticity—the brain's ability to reorganize itself—plays a key role in learning and recovery processes [17]. Indeed, there are several regions or areas of the brain, each with its own special role. The largest division, the Cerebrum, is mainly responsible for reasoning, memory, and voluntary movement [16]. The

cerebellum, located at the back, is responsible for coordination and balance, while the brain stem connects the brain to the spinal cord and helps regulate functions such as respiration and blood circulation [16]. Although the brain is an exceptionally small organ compared to others, it still consumes about 20% of the total energy requirement [17]. Sensation involves the separation of information from sensory input, preparing us to receive environmental stimuli [17]. Additionally, the human brain continuously evolves and reorganizes throughout our lives—a phenomenon known as neuroplasticity [17].

However, the brain remains one of the greatest unsolved mysteries. Scientists continue to explore various aspects of brain function—including consciousness, memory storage, and the management of neurological disorders—due to its complex nature [18]. The brain's intricate structure enables it to respond to numerous stimuli, underscoring its critical role in human physiology [18].

The human brain's cognitive behaviour is defined as the mental functions indispensable for learning, problem-solving, decision-making, and regulating emotions [19]. These processes are critical for mediating experiences, constructing personal perceptions of the environment, and optimizing how we engage with the world [19]. Core to cognitive behavioural therapy are regions such as the Prefrontal Cortex, which governs logical thinking, planning, and decision-making, and the Hippocampus, which is essential for memory and learning [20]. External stimuli are absorbed and processed by these areas, influencing thought processes and behaviour [20]. For instance, memory is used to generate predictions about likely outcomes, just as planning involves selecting the best course of action [20].

Moreover, neuroplasticity—the brain's ability to reorganize itself based on experience or injury—plays a significant role in shaping overall cognitive behaviour [21]. This capacity not only aids in acquiring new skills and talents but also enhances our ability to cope with stress or trauma, contributing to higher emotional intelligence [21].

Understanding the cognitive behaviour of the brain is crucial for treating abnormalities such as ADHD, depression, or Alzheimer's, which disrupt normal functioning [22]. Advances in neuroscience have provided

insights into mental health, learning, and personality enhancement, reinforcing the central role of the brain in human intellect, creativity, and adaptive behaviour.

V. ADVANTAGES

- The BCI system is a promising approach to differentiate and monitor individuals for ADHD as it stays objective, accurate (based on large number of records), personalized and effective in tracking progress overtime.
- The BCI system helps in reducing the delays that occur in diagnosis of an individual for ADHD, especially in cases where symptoms overlap with other conditions (e.g., anxiety, depression)
- It is a non-invasive and simple approach that delivers desirable results without much difficulty and struggle.

VI. DISADVANTAGES

- BCI systems cannot replace traditional methods of diagnosis, as the conditions observed are in the end within a human and the true variations can be judged only by humans itself. They can however be a perfect accompaniment to practice.
- There might be problems with data collection in some cases as some individuals with ADHD might experience discomfort interacting with the equipment and performing tasks.
- There will always be doubts and skepticism regarding this method of diagnosis amongst some clinicians in the initial’s stages of practice.

VII. FINDINGS FROM LITERATURE SURVEY

Sr No.	Title	Blemishes
1.	Design Development of Robotic Exoskeletons in Rehabilitation.	Limited focus on ADHD-specific rehabilitation applications
2.	Exploring the Efficacy of Robotic Assistants with ChatGPT and Claude in	Ethical concerns with AI responses and insufficient data validation.

	Enhancing ADHD Therapy.	
3.	Robotics in Physical Rehabilitation – Review	Lack of ADHD-specific findings and generalized conclusions for robotic therapy.
4.	A Review on Attention Deficit/Hyperactivity Disorder.	Overgeneralized review lacking specific actionable outcomes for ADHD interventions
5.	Adaptive Robotic Systems for ADHD Monitoring.	Real-time adaptability and scalability not validated through extensive user trials.
6.	Real-Time Attention Assessment in ADHD through AI-Driven Robotic Systems.	Limited sample size and absence of control group comparison.
7.	The Role of Robots in ADHD Cognitive Rehabilitation.	Lack of quantitative results and dependence on qualitative feedback.
8.	Cognitive Enhancement with Robots in ADHD Therapy.	Limited scope on general engagement without detailed focus on specific cognitive skills like memory or attention.
9.	Attention Detection and Intervention in ADHD Through Robot-Assisted Therapy	Inadequate real-time feedback validation and dependency on robotic systems without alternative options.
10.	Assessment of a Robotic Assistant for Supporting	Limited scalability and potential distractions caused by

	Homework Activities of Children with ADHD	robotic interfaces.
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VIII. WORKING PRINCIPLE

The main factor that this whole idea revolves around is the Slow Cortical Potentials (SCP). These are slow shifts and changes that are observed in the EEG which indicate actions being performed. The working principle is that individuals with ADHD have a longer response time as opposed to individuals without ADHD, where response time is the time between the initial grasp of action and actual performance of action. There are two different parameters that this is judged by. They are n150 and p400. Generally, all individuals start to grasp the action to be performed around 150 milliseconds of presentation and this can be seen by a negative slope starting around said time (n150). Individuals without ADHD actually begin performing the task around 400 milliseconds after presentation and this can be seen by a positive slope around said time (p400). However, in ADHD individuals, this slope is observed to start after 650-700 milliseconds, which is much after the non-ADHD individuals.

This delay in neurocognitive processing forms the core diagnostic feature that the proposed system aims to monitor and improve. By identifying these SCP deviations in real-time using EEG signals, the system can dynamically respond with therapeutic interventions. Monitoring such minute changes requires a structured and responsive system capable of processing neurophysiological data and adapting based on individual attention levels.

The flowchart (below) outlines a system for monitoring and improving attention in individuals using EEG based neurofeedback and robotic interaction. The process begins with EEG Signal Acquisition, where brain activity is recorded. The data undergoes Signal Preprocessing to filter noise and extract artifacts. Next, Data Segmentation & Feature Extraction identifies relevant EEG patterns. These features are classified using Machine Learning, which determines whether the individual's attention is within the desired range. If attention is below threshold range, a Therapist Interface provides corrective interventions. Or else, Feedback and Robotic Interaction reinforces positive outcomes, closing the loop to improve attention. This system

combines neuroscience, AI, and robotics for therapeutic purposes.

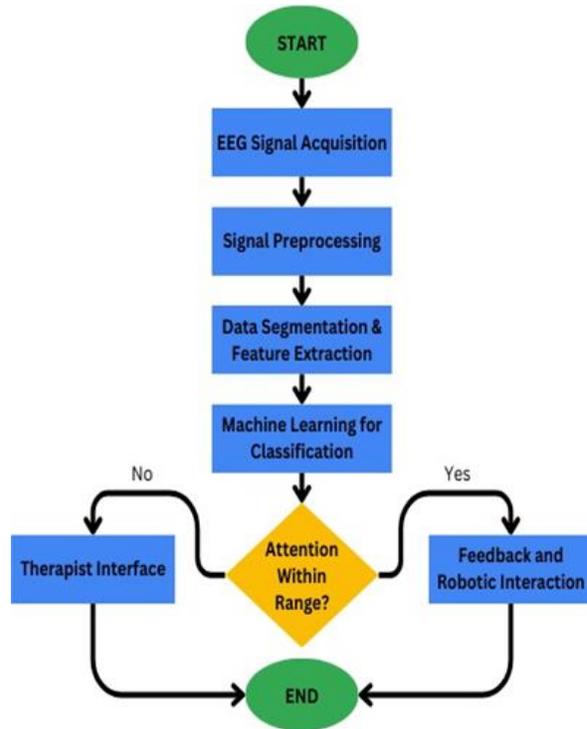


Fig. 1. Flowchart

- EEG Signal Acquisition by the Electroencephalography (EEG) devices record electrical signals from the brain by placing the electrodes on the scalp. These signals capture neuronal activity, enabling real-time monitoring of cognitive states such as attention, relaxation, or focus.
- Signal Preprocessing The raw EEG data contains noise from eye movements, muscle activity, or environmental interference. Signal preprocessing eliminates these artifacts using techniques like filtering and normalization, ensuring clean, reliable data for further analysis.
- Data Segmentation and Feature Extraction from Pre-processed EEG signals are further divided into smaller segments (time windows), and relevant features like frequency bands, power, and amplitude are extracted. These features provide meaningful representations of brain activity for machine learning models.
- Machine Learning for Classification The extracted features are processed by machine learning algorithms trained to identify specific cognitive states. These models classify based on the user's mental state, such

as focused attention or distraction, based on patterns learnt from training data.

- Attention Within Range? The system evaluates whether the user’s attention level meets predefined thresholds. If it falls within the desired range, feedback is given; otherwise, the system routes the process to a therapist interface for intervention.
- Therapist Interface (If "No") When attention is below the desired range, the system activates the therapist interface. This interface provides insights along with recommendations for corrective actions, allowing therapists to guide the individual toward improved focus or attention and overall remedy.
- Feedback and Robotic Interaction (If "Yes") If attention is within the desired range, the system delivers positive reinforcement. This may include robotic interactions along with visual or auditory feedback and rewards to maintain engagement and reinforce the desired cognitive behavior.
- End The process concludes when the session objectives are met. The system then loops back for continuous monitoring or stops, providing a detailed summary of results and outcomes for review by therapists or caregivers.

IX. EXISTING APPLICATION

The existing application/solutions involving Brain Computer Interface and ADHD mainly revolve on training and rehabilitating individuals who have already been diagnosed with ADHD. There are currently no solutions available for the differentiation and identification between an ADHD person and a non-ADHD person [11].

X. DEVELOPMENT

The primary objective is to develop a solution that successfully complements existing traditional methods of ADHD identification and monitoring used in clinical practices [12]. The BCI system would be a promising approach to differentiate and monitor individuals for ADHD as it stays objective, accurate (based on large number of records), personalized and effective in tracking progress overtime.

Response Time: Time between point of grasp of situation and actual performance of action

Observed slopes and meanings:

- Negative slope – Indicates begin of grasping of

situation.

- Negative peak – Situation fully grasped.
- Positive slope – Indicates begin of performance of action.
- Positive peak – Action performed.

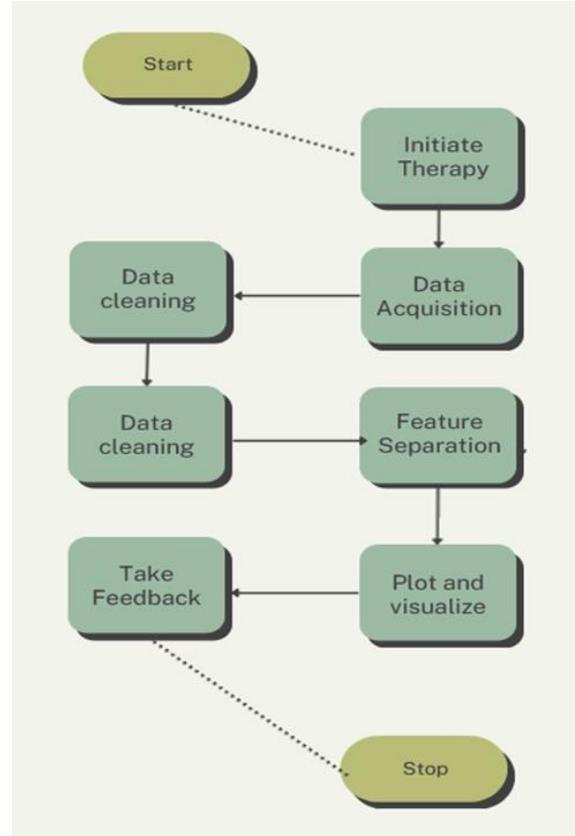


Fig. 2. Concepts And Methods

XI. RESULTS

This section presents the results of EEG signal analysis used for identifying attention response characteristics in individuals with and without ADHD. The primary objective was to differentiate patterns using SCP (Slow Cortical Potentials) derived from EEG data and visualize them in the form of amplitude-to-time graphs.

Figure 3 shows the amplitude-to-time graph for a normal person. This graph depicts the brain’s electrical activity over time, representing multiple trial runs. The red line indicates the averaged SCP waveform, which helps identify critical temporal features of cognitive response. In a normal subject, the waveform begins to show a downward trend (negative slope) near 150 milliseconds, known as the n150 point, representing the

beginning of task comprehension. Around 400 milliseconds, a visible upward trend (positive slope) appears, corresponding to the p400 point, marking the start of action execution. These patterns are consistent with efficient cognitive processing and indicate an appropriate attention response in neurotypical individuals.

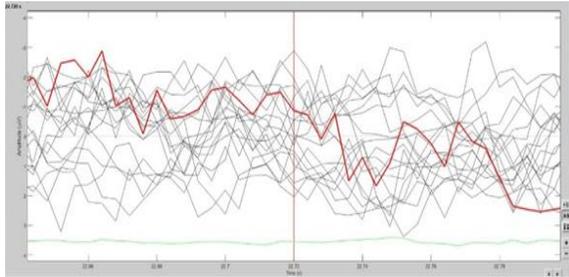


Fig. 3. Amplitude to time graph for a normal person

Figure 4 shows the amplitude-to-time graph for a person suffering from ADHD. This graph represents the SCP activity in a subject diagnosed with ADHD. In contrast to the normal subject shown in Figure 1, the waveforms here lack a clear and timely transition into the n150 and p400 patterns. The expected negative and positive slope changes are significantly delayed or flattened, indicating an impaired or slower cognitive response. The red vertical line marks the stimulus presentation, but there is little or no immediate downward or upward slope that signifies task grasp and execution. This flattened response is consistent with attention-related impairments, which are characteristic in ADHD subjects and validates the delay in their neurofeedback response time.

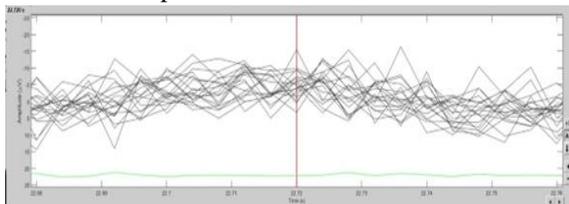


Fig. 4. Amplitude to time graph for a person suffering from ADHD

XII. CONCLUSION

Research and development in Brain-Computer Interfaces (BCIs) have seen significant advancements in recent years. Technologies have matured, and the number of organizations contributing to this field has grown rapidly. What was once limited to laboratory

experiments is now transitioning into commercial and therapeutic applications.

This paper aimed to identify the gaps in current BCI-based robotic systems for ADHD rehabilitation and explore a comprehensive approach to improve attention-monitoring and intervention techniques. Through an extensive literature survey, we examined existing work in robotic-assisted therapy, AI-driven cognitive monitoring, and adaptive systems for ADHD management.

The main objective was to explore and design an effective approach for ADHD rehabilitation by leveraging robotic systems, BCI technologies, and AI integration. From the literature survey, it is evident that many existing systems lack ADHD-specific validation, scalability, real-time adaptability, and often overlook crucial cognitive skills such as memory and attention. Ethical concerns and dependency on robotic systems without alternatives were also significant issues.

Based on the review and analysis, this work proposes a direction for building a more responsive and personalized ADHD rehabilitation system. The identified limitations serve as design guidelines to overcome these issues in future implementations.

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