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THE EFFICACY OF NEUROFEEDBACK ON NEUROPHYSIOLOGICAL REGULATION AND FUNCTIONAL OUTCOMES IN CHILDREN WITH DEVELOPMENTAL DISORDERS: A LONGITUDINAL MIXED-METHODS ANALYSIS

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ABSTRACT
This study analysed a long-term audio-visual neurofeedback training program for Malaysian children with developmental disorders. Seven children aged four to eight completed over 72 sessions across six months to three years. A qualitative quasi-experimental design used pre- and post-test that combines EEG brainwave data with qualitative observations and parent interviews. The Brain Function Analysis framework helped analyse the EEG data. Quantitative results showed significant improvements in Brain Arousal, Physical Stress, and Mental Stress ($p<0.05$) and these changes matched qualitative findings of improved attention, speech, and behavioural regulation. Long-term neurofeedback training is an effective non-invasive program; it promotes lasting brain changes for functional improvements. The study highlights the value of combining brain data with qualitative observations and the BFA framework for personalised treatment and outcome measurement.
Keywords: Neurofeedback Training (NFT), Developmental Disorders, Neurophysiological Dysregulation, Electroencephalography (EEG), Self-Regulation

1. INTRODUCTION

1.1. The Escalating Challenge of Developmental Disorders

Developmental disorders are a growing public health issue worldwide and affect millions of children and families (Doernberg & Hollander, 2016). These conditions involve inattention, speech delays, and behavioural dysregulation. These conditions hinder children's learning, social integration, and quality of life. The symptoms are interconnected. For example, attention problems can slow language learning and communication issues can lead to behavioural outbursts.

This global issue is also present in Malaysia. The 2019 National Health and Morbidity Survey reported a 4.7% increase in Malaysian children with functional difficulties. National Special Education Programme enrolment increased every year. Students with learning disabilities made up over 80% of this group each year. These numbers highlight an urgent need for effective interventions to cater for children's neurodevelopmental needs.

1.2. Limitations of Conventional Intervention Paradigms

Traditional care for developmental disorders combines psychostimulants and behavioural therapy. However this approach has limitations. Medication has side effects and its long-term benefits are uncertain. Behavioural therapies are time-consuming and resource-intensive because their effects often diminish after the programme ends. This highlights the need for more lasting solutions especially since specialised therapists are scarce in Malaysia.

1.3. Neurofeedback Training (NFT): A Brain-Based Approach to Self-Regulation

NFT is a non-invasive and non-drug biofeedback method. It uses real-time EEG displays to teach self-regulation of brain function and addresses conventional method limitations through operant conditioning (Mirifar et al., 2017). When a person's brain produces desired brainwave patterns for a target state like calm focus, they get positive sensory feedback (Hammond, 2011; Sho'ouri, 2021). Repeated sessions strengthen the neural pathways for these healthier patterns and promote lasting changes in brain function.

NFT works because of neuroplasticity. Neuroplasticity is the brain's ability to reorganize its structure and connections based on experience (Sherlin et al., 2011). NFT does not just manage symptoms. It targets the underlying neurophysiological dysregulation by guiding the brain toward more efficient states. This method supports improvements in developmental, cognitive and behavioural control.

1.4 Research Purpose

This study's main goal is to provide a complete longitudinal mixed-methods analysis of a long-term NFT program for children with developmental disorders. The research combines objective neurophysiological data with rich qualitative observations to understand the changes from this program. The study uses the new Brain Function Analysis (BFA) framework to analyse EEG data. This system turns complex brainwave data into a holistic and clinically useful profile of brain function. This research evaluates the effectiveness of a specific neurofeedback training and confirms the utility of an innovative analytical framework for tracking neurophysiological change.

1.4.1 Research Questions

The Research Questions (RQs) of this study:

RQ1: What are the NFT effects on the children's brainwave patterns with developmental disorders as measured by the Brain Function Analysis (BFA) framework metrics (Brain Arousal, Physical Stress, and Mental Stress)?

RQ2: What are the NFT functional observable results in attention, speech development and behavioural regulation?

1.4.2 Research Objective

This study is expected to achieve the following research objectives:

RO1: To quantify the effects of NFT on the brainwave patterns of children with developmental disorders by measuring Brain Arousal, Physical Stress, and Mental Stress using BFA.

RO2: To evaluate the NFT's functional observable result in attention, speech development, and behavioral regulation.

2. LITERATURE REVIEW

2.1. EEG Frequency Bands as Biomarkers of Cognitive and Affective States

An EEG records constant electrical signals in the brain. The signals are sorted into different frequency bands to show mind and awareness states. These bands act as important markers to check brain function (Mirifar et al., 2017). The Brain Function Analysis (BFA) framework can measure multiple wave frequencies for holistic reporting.

Alpha (α) waves (8–12 Hz) are strongest (Mirifar et al., 2017) when a person awakens and relaxes with their eyes shut. Alpha activity helps the brain ignore unneeded information to filter distractions and hold focus. The Sensorimotor Rhythm (SMR) is a type of beta wave recorded at 12–15 Hz over the sensorimotor cortex. SMR is needed to achieve a state of "calm focus" (Afrash et al., 2023). Higher SMR activity is connected to better attention with less impulsivity and anxiety (Fuentes-García & Villafaina, 2024).

Beta (β) waves (13–30 Hz) show an alert and active mind. The BFA framework splits Beta into two parts which are mid beta and high beta. Mid-Beta (16–20 Hz) links to solving problems. High-Beta (21–30 Hz) relates to stress, anxiety, and body tension. Neurofeedback training tries to raise Mid-Beta and lower High-Beta (Mirifar et al., 2017). Too much Theta (θ) wave activity (4–8 Hz) while awake is a sign of sleepiness and poor focus (Mirifar et al., 2017). The Theta/Beta Ratio (TBR) measures the balance between slow theta waves and fast beta waves. A high TBR is a major QEEG marker for ADHD because it shows attention problems and an under-active cortex (Lubar & Shouse, 1976).

2.2. The Mechanism of Audio-Visual Neurofeedback

This NFT protocol uses an intentional and theoretically sound audio-visual feedback method. The brain processes combined audio-visual information more efficiently than single-sensory inputs and this creates an additive effect that improves learning and neural processing (Shams & Seitz, 2008; Perronnet et al., 2017). This multi-sensory approach maximises engagement and drives neuroplastic change (Marzbani et al., 2016). Simultaneous audio and visual feedback provides a clear reward for the brain. Children benefit from this directness because they may struggle with abstract feedback. Using familiar media like cartoons makes training an engaging activity and maintains motivation, which assists in the study's intervention (Micoulaud-Franchi et al., 2014). This protocol addresses a research gap regarding the ongoing clinical importance of NFT, especially in the lack of long-term mixed-methods frameworks in Malaysia. This research aims to provide such long-term data from a local context.

3.0 METHODOLOGY: A LONGITUDINAL MIXED-METHODS DESIGN

3.1. Research Design

A multi-pronged data collection strategy captured neurophysiological and functional changes. EEG data was collected pre-intervention, following six months of training, and during a one-to-three-year follow-up. The BFA programme processed raw EEG data. The Korea Research Institute of Brain Science validated the BFA framework and data with an average correlation of 0.942 ($p<0.01$) to the original signal, which ensured accuracy. The BFA framework is the main tool for interpreting quantitative QEEG data. It translates complex raw EEG signals into eleven integrated and scientifically validated metrics for a holistic brain function profile.

A qualitative study involved systematic observations of children during NFT sessions. A protocol documented key indicators for attention, speech, language use and behavioural regulation. Semi-structured interviews with parents gathered in-depth information on their children's progress and the intervention's effects.

3.2. Participant Profile

Seven children (four males, three females) aged 4 to 8 years from Selangor, Malaysia were recruited for the study. All participants had developmental disorders and showed a mix of inattention, speech and language delays and significant behavioural challenges. The samples including participants diagnosed autism spectrum disorder (ASD), Global Developmental Delay (GDD), attention deficit hyperactivity disorder (ADHD), speech delay and learning disabilities. Table 1 provides a detailed summary of participant characteristics at the start

Table 1. Participant Demographics and Baseline Characteristics

ID	Age	Gender	Diagnosis / Presenting Symptoms	Key Baseline Challenges	Inattentive	Speech and Language Delay	ADHD/ ADD	Behaviour: Frequent Temper Tantrums	OKU Card Holder
PN1	8	M	ASD with non or little verbal	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	Yes	Yes	Yes
PN2	5	F	Slow in development with non-verbal (premature infant - twin)	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	No	Yes	No
PN3	7	F	ASD with non-verbal	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	No	Yes	No
PN4	4	M	Speech and language delay (No speech from mouth) with less eyes contact	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	No	No	No
PN5	6	F	GDD with cerebellar ataxia and basal ganglia necrosis. Speech and language delay (No speech from disorder) and physical disorder	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	No	No	No
PN6	7	M	ASD with non or little verbal	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	Yes	Yes	Yes
PN7	7	M	ASD with non or little verbal	Inattention, Speech Delay, Temper Tantrums	Yes	Yes	Yes	Yes	Yes

Source: Author own's work

3.3 The Neurofeedback Intervention Protocol

The intervention took place at a specialized centre in Selangor, Malaysia. Data acquisition was conducted using the Brain Science EEG headband (Brainsc Headband). The Brainsc Headband is a non-invasive device integrated with the Brainscience Neurofeedback program. Two electrodes were placed on the forehead during assessment and training. These corresponded to the Fp1 and Fp2 sites, specifically targeting electrical activity in the prefrontal cortex. A third reference electrode attached via an ear clip. The AI-driven system uses algorithms for personalised training and provides high-fidelity brainwave data analysis with 0.942 signal reliability ($p<0.01$).

Participants attended at least 12 minute to 45-minute sessions monthly. The intervention lasted from six months (72 sessions) to over three years. This high-dose approach is consistent with research linking greater cumulative training time to better outcomes (Onagawa et al., 2023).

During sessions participants watched age-appropriate media and the system provided real-time operant conditioning feedback. When brainwave patterns deviate from the target feedback, it is withdrawn and prompting adjustment to restore the reward (Afrash et al., 2023). Successful self-regulation is rewarded with continued media. Using enjoyable media is effective in paediatric neurofeedback because it maximises engagement.

3.4 Data Collection and Analysis

A multi-pronged data collection strategy captured neurophysiological and functional changes during the intervention. EEG data were collected at three time points. Initially is pre-intervention (baseline), after six months of training, and lastly at a final follow-up (one to three years post-baseline). The BFA programme processed and analysed raw EEG data, interpreting complex raw EEG signals into 11 scientifically validated metrics for a holistic and clinical profile of brain function.

The researcher also conducted a qualitative study through systematic observations during NFT sessions. A protocol was used to document attention, speech, language use, and behavioural regulation. Semi-structured interviews with parents gathered in-depth information on their children's progress and NFT's effects.

4. RESULTS: A DUAL-LENS ANALYSIS OF INTERVENTION OUTCOMES

4.1 Part A: Quantitative Neurophysiological Transformation

Longitudinal QEEG analysis and the BFA framework revealed significant neurophysiological improvements within the participant group.

4.1.2 Detailed Statistical Analysis

Detailed statistical analysis confirms the significance of these improvements over time.

Brain Arousal

Neurofeedback training significantly decreased participants' Brain Arousal. Scores dropped from 4.53 (SD=1.70) before training to 2.63 (SD=.25) after six months, $t(6) = 2.84$, $p <.05$. Furthermore, scores decreased to 2.54 (SD=.22) after more than six months, $t(6) = 2.93$, $p <.05$ which indicates a sustained reduction. Tables 2 and 3 describe brain arousal data.

Table 2. Descriptive Statistics for Brain Arousal (N=7)

Brain Arousal	N	Mean	Std. Deviation	Std. Error Mean
Before Training	7	4.53	1.70	.64
After Six Month Training	7	2.63	.25	.10
> Six Month Training	7	2.54	.22	.08

Table 3. Paired-Samples t-Test for Brain Arousal

Comparison	Mean Difference	Std. Deviation	t	df	p-value
Before vs. After 6 Months	1.90	1.77	2.84	6	0.03
Before vs. After > 6 Months	1.99	1.80	2.93	6	0.03

Physical Stress

Neurofeedback training significantly reduced physical stress, and scores decreased from 60.60 pre-training to 44.92 after six months post-training. Scores further dropped to 39.11 after more than six months demonstrating a progressive reduction. Tables 4 and 5 describe physical stress data.

Table 4. Descriptive Statistics for Physical Stress (N=7)

Physical Stress	N	Mean	Std. Deviation	Std. Error Mean
Before Training	7	60.60	11.40	4.31
After Six Month Training	7	44.92	13.61	5.14
> Six Month Training	7	39.11	12.25	4.63

Table 5. Paired-Samples t-Test for Physical Stress

Comparison	Mean Difference	Std. Deviation	t	df	p-value
Before vs. After 6 Months	15.68	4.11	10.10	6	.00
Before vs. After > 6 Months	21.49	13.26	4.29	6	.01

Mental Stress

Mental stress significantly decreased after training and dropping from M=5.64 (SD=1.54) to M=2.76 (SD=.81) at six months, $t(6)=7.72$, $p < .001$. This improvement was sustained and slightly enhanced after six months (M=2.52, SD=.54) and remaining highly significant from baseline, $t(6)=6.64$, $p < .001$. This demonstrates neurofeedback training's effectiveness in reducing mental distraction and improving cognitive efficiency. Tables 6 and 7 describe mental stress data.

Table 6. Descriptive Statistics for Mental Stress (N=7)

Physical Stress	N	Mean	Std. Deviation	Std. Error Mean
Before Training	7	5.64	1.54	.58
After Six Month Training	7	2.76	.81	.31
> Six Month Training	7	2.52	.54	.20

Table 7. Paired-Samples t-Test for Mental Stress

Comparison	Mean Difference	Std. Deviation	t	df	p-value
Before vs. After 6 Months	2.88	0.99	7.72	6	.00
Before vs. After > 6 Months	3.12	1.24	6.64	6	.00

Data Summary

Table 8 summarises the longitudinal changes in key BFA metrics for each participant and shows the magnitude and consistency of neurophysiological changes over time.

Table 8. Longitudinal Changes in Key BFA Metrics for All Participants

ID	Metric	Before NFT	After 6 Months	After >6 Months
PN1	Brain Arousal (Ratio)	6.6/6.2	2.74/3.24	2.31/2.59 (at 2.5 years)
	Physical Stress (L/R)	53.2/60.8	39.26/40.56	13.18/31.61 (at 2.5 years)
	Mental Stress	3.9	2.49	2.49 (at 2.5 years)
PN2	Brain Arousal (Ratio)	5.1/5.3	2.6/2.4	2.6/2.5 (at 1 year)
	Physical Stress (L/R)	72.1/69.5	62.32/63.66	59.48/60.31 (at 1 year)
	Mental Stress	8.2	4.23	3.63 (at 1 year)
PN3	Brain Arousal (Ratio)	5.2/5.3	2.6/2.6	2.1/2.4 (at 2.25 years)
	Physical Stress (L/R)	68.7/62.0	43.35/47.74	23.46/57.70 (at 2.25 years)
	Mental Stress	5.5	3.11	2.52 (at 2.25 years)
PN4	Brain Arousal (Ratio)	5.9/6.3	2.5/2.2	N/A
	Physical Stress (L/R)	55.2/71.0	44.6/44.61	N/A
	Mental Stress	5.1	2.48	N/A
PN5	Brain Arousal (Ratio)	4.4/4.1	2.4/2.5	2.1/3.2 (at 2 years)
	Physical Stress (L/R)	30.7/42.3	16.71/21.19	24.76/22.64 (at 2 years)
	Mental Stress	4.25	1.55	1.1 (at 2 years)
PN6	Brain Arousal (Ratio)	2.1/2.4	2.72/3.24	2.5/2.8 (at 3 years)

ID	Metric	Before NFT	After 6 Months	After >6 Months
	Physical Stress (L/R)	65.2/66.5	49.18/49.97	16.72/37.95 (at 3 years)
	Mental Stress	5.4	2.68	1.9 (at 3 years)
PN7	Brain Arousal (Ratio)	2.4/2.1	2.38/2.75	2.3/2.7 (at 2.5 years)
	Physical Stress (L/R)	65.0/66.2	51.82/53.89	31.04/53.98 (at 2.5 years)
	Mental Stress	7.15	2.81	2.41 (at 2.5 years)

Note: Data synthesized from individual case descriptions. Brain Arousal is presented as Left/Right hemisphere ratios. Physical Stress is presented as Left/Right hemisphere scores. Mental Stress is the average of Left and Right hemisphere scores.
Source: Author own's work

Analysis of Specific EEG Frequency Bands

Post-training brainwave analysis showed the NFT programme significantly increased Alpha, SMR, and Low Beta power. It is correlated with observed functional improvements. Increased alpha wave power improves endurance, stability, and fatigue recovery. Increased SMR wave power enhances attention, sociality, and sensory processing. Increased low beta wave power boosts concentration, drive, and cognitive output. The program succeeded by enhancing beneficial brainwave patterns and reducing dysregulated activity. These changes appeared in BFA stress and arousal metrics.

Individual Case Analysis

A 3D brainwave graph of PN6 illustrated a significant decrease in disorganised, high-frequency activity and aberrant fast-wave infiltration after 430 sessions. Changes in Alpha Wave Power visually reflected these improvements and moved from fluctuating to stable. This corresponded to enhanced higher-order cognitive functions, specifically comprehension and memory consolidation.

4.2 Part B: Qualitative Manifestations of Developmental Progress

QEEG data documented neurophysiological transformations. These changes matched profound and life-altering improvements in the children's daily function. A qualitative approach that using systematic observation and detailed parent interviews can capture these functional outcomes to reveal three primary themes of developmental progress.

4.2.1 Theme 1: Enhanced Attention and Focus

Improved attention and focus was a primary observation to confirm children's improvement. All participants sustained attention better and sitting tolerance. Children who previously could not sit still now completed full 45-minute NFT sessions without motor restlessness. Eye contact became more consistent and purposeful. Besides that, participants gained skill in structured tasks that requiring focus, such as pre-writing exercises.

Parents' reports confirmed these observations by describing children as more "present" and engaged. One parent noted that "His attention did improve and will easily notice things around him instead of last time. Previously, he was just all over the place and didn't notice his surroundings" (PN6's parent). Another parent shared, "His concentration is very long and he can sit in a chair for more than one hour without moving" (PN7's parent). This new focus extended to social interaction. Another parent explained that "She had eye contact and she hadn't before" (PN2's parent). The focus improvement allowed children to follow multi-step instructions, complete homework, and join family activities that were previously impossible.

4.2.2 Theme 2: Emergence of Speech and Communication

Non-verbal children with speech delays began to communicate, understand language, and use words. Parents reported powerful stories of these changes like hearing "mama" or asking for toys. These actions reduced frustration and improved interactions.

4.2.3. Theme 3: Improved Behavioural and Emotional Regulation

Children's behaviour and emotional regulation improved. Fewer, shorter, and less intense temper tantrums daily. They became less sensitive to loud noises and participated more in activities. Hyperactivity decreased as calmer conduct replaced it. Parents reported a more peaceful home life due to reduced aggression and increased cooperation. Improved tolerance and self-control strengthened children's relationships with siblings and friends.

4.2.4 Synthesis of Neuro-Behavioural Findings

Combining brain data with real-world observations offers a complete picture of a program's impact. Brain scans reveal invisible change. Parent and observer accounts show changes affect a child's learning, speech and social interaction. A decrease in physical stress in the brain correlates with fewer tantrums and less hyperactivity, which links brain activity to observed progress.

5. DISCUSSION

5.1 Synthesis of Findings: A Neuro-Behavioural Model of Change

This long-term study demonstrates that audio-visual neurofeedback significantly improves children with complex developmental disorders. Combined EEG brain data and qualitative reports illustrate a model where functional gains in attention, speech and behaviour directly result from the brain's enhanced self-regulation through training. Positive changes in BFA brain metrics cause these behavioural improvements. The brain learns to manage its activity through extensive practice and leading to improved attention, emotional regulation and actions in daily life.

5.2 Contextualizing Outcomes within Contemporary Neuroscience (2020–2025)

Neurofeedback results in this study align with current scientific literature.

SMR and Beta protocols are effective for attention and self-regulation disorders. Research by Afrash et al. (2023) supports SMR-enhancement and Alpha-suppression protocols because they show better long-term retention than Mu-suppression. This study's positive long-term outcomes further validate this approach.

The intervention's duration and intensity are a critical strength. Participants completed a minimum of 72 sessions (over 54 hours or 3,240 minutes) of training. This exceeded the 125-minute threshold identified by Onagawa et al. (2023) for potential performance improvements. The robust and lasting changes observed highlight the importance and long-term NFT for meaningful neuroplasticity in the pediatric population.

The engaging bimodal audio-visual feedback system is a significant methodological contribution. Direct comparisons between unimodal and bimodal feedback systems were historically lacking (Mirifar et al., 2017) . Recent research supports the enhanced efficacy of a multi-sensory approach. Pilot studies comparing audio-visual to visual-only neurofeedback for attention enhancement show that audio-visual feedback leads to more significant improvements in neurological activity and behavioural attention tasks. A 2024 study reported that an audio-visual group increased global EEG beta activity and achieved higher scores and faster reaction times on the Stroop task compared to a visual-only group. These findings support the present study's protocol, suggesting that combining auditory and visual stimuli creates a more potent learning environment. High engagement and compliance observed in this study's pediatric cohort further underscore this point, and transforming training into an intrinsically motivating experience is key for lasting neuroplastic change (Fuentes-García & Villafaina, 2024).

5.3 Addressing Study Limitations and Future Directions

Acknowledge study limitations because a sham-neurofeedback control group was not included, and this can frame results and guide future research.. Without such a control it is difficult to definitively disentangle the specific effects of neural self-regulation from non-specific therapeutic factors such as the structured attention from a therapist, the routine of attending sessions and participant or parent expectations (the placebo effect).

Secondly, the small sample size (N=7) while appropriate for an in-depth qualitative case-study approach inherently limits the statistical power and generalizability of the quantitative findings. The participants' diverse diagnoses make it challenging to attribute effects for clinical profiles.

These limitations illuminate a clear path for future research. A larger randomized controlled trial with a credible sham-NFT control group is the next logical step to provide high-level evidence. Future research should also directly compare the efficacy of bimodal audio-visual feedback against unimodal conditions to isolate the multi-sensory approach's contribution. Adopting the BFA framework as standardized outcome measures could improve comparability across studies and foster a unified evidence base in clinical neurofeedback.

6. CONCLUSION AND IMPLICATIONS

6.1. Primary Conclusion

A long-term and high-dose audio-visual NFT program improved neurophysiological regulation and functional behaviours in developmental disorders children. Quantitative EEG data (BFA framework) and qualitative data validated the program's efficacy. The findings suggest that NFT helps children to train their brain for more stable and efficient states.

6.2. Recommendations

This study offers actionable recommendations for policymakers and families.

For Clinicians: The BFA framework effectively translates neurophysiological data into a clinical profile and aid intervention for personalized treatment. Engaging audio-visual feedback is recommended for pediatric clients.

For Policymakers: NFT is a viable non-pharmacological intervention for children with developmental disorders. Government bodies like Malaysia's KPWKM should integrate NFT into early intervention programs and expand access to evidence-based non-medicinal options.

For Parents and Educators: Meaningful change requires long-term commitment and a supportive home environment. Addressing psychosocial barriers such as stigma and lack of information is crucial. Public awareness and educational resources are needed to empower parents and combat developmental disorders and neurofeedback misconceptions.

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