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CLINICAL TRIAL REPORT

Impact of Mobile Neurofeedback on Internet Addiction and Neurocognitive Function in Neurotypical Children: Double-Blind, Sham-Controlled Randomized Clinical Trial

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Objective: The purpose of this study was to evaluate the positive impact of mobile neurofeedback (MNF) in neurotypical children compared to sham mobile neurofeedback.

Methods: Neurotypical children aged 10–15 participated in the study. All subjects were assessed using the Kiddie Schedule for Affective Disorders and Schizophrenia Present and Lifetime Version Korean Version (K-SADS-PL-K) and confirmed to have no psychiatric symptoms. The participants were randomly assigned to the MNF active (N=31) or sham control (N=30) groups. The MNF program was administered using a mobile app for 30 min/day, 3 days/week, for 3 months. All participants and their parents completed self-report scales and participants complete neurocognitive function assessments including the continuous performance test, Stroop, children's color trails test-1 and 2, and intelligence test at baseline and after the 3-month MNF program.

Results: This study involved 61 participants (mean [SD] age, 11.24 [1.84] years; 30 male participants [49.2%]). To verify the difference between the MNF group and the sham group, 2(MNF-Sham) X 2(Pre-Post) repeated measures ANOVA was performed. The main effect of the K-scale (Korea Internet addiction scale) between-group factor (MNF vs Sham) was not significant, but the main effect of the within-group factor (Pre vs Post) was significant (F=7.595, p=0.008). The interaction effect of between-group factors and within-group factors was also significant (F=5.979, p=0.017). In other self-reported scales of children and parents and neurocognitive function assessments, there was no significant difference between the two groups.

Conclusion: Active mobile neurofeedback significantly improved children's K-scale score compared to the sham group. Therefore, mobile neurofeedback could be an easy-to-access therapeutic option for children at risk of Internet addiction. On the other hand, there was no significant difference in other scales and neurocognitive function. A 3-month intervention may not have been long enough to cause change, so longer interventions are needed for confirmation.

Keywords: mobile neurofeedback, double-blind randomized clinical trial, neurotypical children, internet addiction

Introduction

Neurofeedback is a non-invasive therapeutic approach, a subtype of biofeedback, where patients learn to self-regulate their brainwaves by perceiving them through monitoring equipment. This method empowers patients to control their brainwave patterns as intended through training.[1] Patients' brainwave patterns are transformed into immediate visual or auditory feedback, such as sounds or animations, allowing them to receive real-time information about their brainwave states. By receiving appropriate rewards and undergoing repetitive learning, patients become proficient in regulating their brainwaves. This approach is rooted in theories of operant conditioning and other learning effects.[2] Through such learning effects, neurofeedback training induces neuroplasticity, preventing pathological synaptic strength or oscillatory states from occurring in the brain.

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Furthermore, it is based on the fundamental principle that by promoting normalization of brain activity and self-regulation, it can lead to improved cognitive and behavioral control in children with ADHD who may be lacking in these aspects.

The most extensively studied psychiatric disorder in which neurofeedback has been widely applied is Attention Deficit/Hyperactivity Disorder (ADHD). ADHD is characterized by core symptoms, including inattention, hyperactivity, and impulsivity. Children with ADHD are known to exhibit deficits in executive functions, such as working memory, inhibitory control, and planning, in addition to these core symptoms, as compared to typically developing children.[3] In addition to pharmacological treatment, non-pharmacological approaches such as psychiatric education, behavioral parent training (BPT), cognitive behavioral therapy, and social skills training programs can also be used to treat ADHD.[4] Neurofeedback has been proposed as a prominent alternative in this context, garnering ongoing attention from researchers. An advantage of neurofeedback lies in its non-invasive nature, with minimal potential for side effects in patients.[5] Neurofeedback was initially developed based on the research findings of Lubar et al, involving a training method that reduces theta activity in the frontal and parietal lobes while promoting beta activity.[6] During neurofeedback training for children with ADHD, they are rewarded with improved performance in computer games or the sound of a success signal. This encourages ADHD children to learn how to regulate their theta and beta brainwaves and maintain a stable EEG state. Furthermore, the therapeutic effects of neurofeedback have been reported not only for ADHD but also for conditions such as stroke, insomnia, depression, and obsessive-compulsive disorder.[7]

Among various mental disorders, research on the effects of neurofeedback in relation to addiction also continues to advance.[8] Specifically, neurofeedback protocols based on brainwave assessments have primarily focused on substance use disorders. EEG-based neurofeedback has shown promising outcomes in alcohol use disorder by reducing impulsivity, recklessness, and risk aversion, and in nicotine addiction by decreasing smoking rates and cravings.[9] Indeed, EEG-NFB has been included as an effective treatment modality for substance use disorders in guidelines for the clinical efficacy assessment of psychophysiological interventions.[10] Conversely, biofeedback protocols using peripheral measurements, primarily based on heart rate variability, have centered on behavioral addictions.[11] Therefore, although there have been limited studies applying neurofeedback to internet addiction patients, research utilizing neurofeedback as an additional tool for the treatment of alcohol use disorder has demonstrated effects, influencing attentional bias or lack of inhibition.[12] Studies observing the brainwave characteristics of internet addiction have revealed shared neurophysiological traits with other addictions.[13,14] Consequently, there exists a possibility that the contributions of neurofeedback evident in other addiction disorders may also manifest in internet addiction.

Apart from clinical applications, research is also exploring the realms of "optimal" or "performance enhancement" in healthy individuals. One study introduced an approach to boost golf performance by employing personalized real-life neurofeedback during golf putting.[15] Another investigation harnessed neurofeedback training via EEG to optimize attention levels in expert rifle shooters, and the results demonstrated an enhancement in shooting performance associated with specific EEG patterns. This suggests that particular brain states are conducive to achieving "successful" shots, and neurofeedback training can influence these states.[16] Nevertheless, research on the effects of neurofeedback in healthy children and adolescents remains limited. The period of childhood and adolescence is marked by significant brain neuroplasticity compared to adulthood, making it an opportune time to harness the potential of neuroregulatory therapies like neurofeedback.[17] Moreover, it is anticipated that conditioning processes and motivation would be more manageable in healthy children and adolescents who possess superior attention and self-regulation abilities compared to those with ADHD. Nevertheless, for these assumptions to be substantiated, rigorous scientific verification, including double-blind experiments and sham control groups, is imperative.

The objective of this study was to ascertain the therapeutic impact of mobile neurofeedback (MNF) in neurotypical children when compared to sham MNF. Clinical assessments were conducted both before and after the MNF intervention, and the effectiveness of the intervention was to be validated through these evaluations.

Methods

Participants

The study included child participants ranging from 8 to 15 years of age, who were recruited from the Department of Psychiatry at Daegu Catholic University Medical Center between 2019 and 2021. All individuals underwent assessments

using the Korean version of the Kiddie Schedule for Affective Disorders and Schizophrenia Present and Lifetime Version (K-SADS-PL-K) to confirm the absence of psychiatric symptoms. Exclusion criteria comprised a history of congenital genetic diseases, brain damage, neurological disorders, and psychiatric conditions such as schizophrenia spectrum disorder, autism spectrum disorder, obsessive-compulsive disorder, major depressive disorder, or bipolar disorder. Additionally, participants with an IQ below 70, as determined by the Korean-Wechsler Intelligence Scale for Children-Fourth Edition (K-WISC-IV), were excluded from the study.

Prior to their involvement, all children and their parents were provided with comprehensive information about the study. Written consent was obtained for the medical use of test results and the participation of the children in the research. The study protocol was reviewed and approved by the Institutional Review Boards of Daegu Catholic University Medical Center (CR-19-064), and it adhered to the principles outlined in the Declaration of Helsinki (World Medical Association: Ethical Principles for Medical Research Involving Human Subjects, 1964).

Trial Design

This study employed a double-blinded randomized, sham-controlled trial design to investigate the impact of MNF on neurotypical children. In each group, participants were randomly allocated to receive either the active MNF intervention or a sham intervention. This allocation was carried out using a web-based randomization program provided by the Medical Research Collaborating Center (MRCC) at the Biomedical Research Institute of Seoul National University Hospital (https://mrcc.snuh.org/). Through this process, participants were randomly divided into the MNF active group (N=31) or the sham control group (N=30). The random assignment was maintained in a blinded manner for the researchers, clinicians, children, and their parents until the conclusion of the study. Before the randomization process, all participants underwent self-report assessments, K-WISC-IV, Stroop, Advanced Test of Attention(ATA), Children's Color Trails Test(CCTT), and electroencephalography. These same assessments were repeated after the completion of the 3-month intervention. The trial was registered at ClinicalTrials.gov as MDCR-19-007.

Intervention

The neurofeedback headsets employed in this study were developed by OmniCNS and can be found at (https://brain.omnifit.co.kr/en/index). These headsets featured 2 channels and a reference sensor, utilizing a dry EEG method to measure EEG signals at a rate of 250Hz. These signals were subsequently transformed into the frequency domain through Fourier transform, allowing the assessment of power across a wide range of frequencies from theta (4–8Hz) to gamma (30–51Hz). EEG power was recorded at 2-second intervals, and feedback was provided in the form of various activities (levitation, running, turning a fan, lifting weights, bursting balloons) based on the level of attention, determined by the Low beta + Middle beta / Theta Power ratio. The neurofeedback game was structured into three levels, each requiring a specific level of Low beta + Middle beta / Theta Power. The neurofeedback program utilized for the sham control group presented training outcomes generated randomly, dissociated from the actual measurements obtained by the neurofeedback device. The distribution of training outcome ratings was meticulously adjusted to mitigate extreme values, thereby ensuring participants encountered no perceptible discrepancies. For example, within the neurofeedback score range of 0 to 100, divided into five tiers, the highest and lowest score levels were deliberately minimized, while median scores were more frequently displayed. This methodology was devised to maintain the indistinguishability of the sham condition from genuine training, thereby preserving uniformity in user experience.

Each participant was provided with a MNF application and equipment and received approximately an hour of training on how to use them. The training was conducted by psychiatrists well-versed in MNF, ensuring that participants received education from experts with sufficient knowledge of the subject. During this training, the research team concluded that the participants were able to grasp the concept and adequately learned the neurofeedback processes involved in the study. Following the training, participants engaged in neurofeedback games through the Omnifit Brain application using the provided headsets and their personal smartphones for a duration of 12 weeks. The neurofeedback games were conducted three times a week, with each session lasting 10–20 minutes and two sessions per day. Four different types of games were offered, all based on the theta/beta ratio. Participants were free to choose the game they found most engaging, and there were no restrictions on game selection.

The implementation of the neurofeedback intervention was monitored through device connection and usage logs. If participants encountered any difficulties in using the application, they had the option to seek assistance from their parents. An assessment of the actual usage time was conducted every two weeks, and if the participation rate fell below 75%, encouragement was provided through telephone interviews to enhance engagement. Additionally, assessments were made regarding any discomfort experienced during usage.

Measures

Korean Wechsler Intelligence Scale for Children-Fourth Edition (K-WISC-IV)

The K-WISC-IV is a standardized assessment tool designed to evaluate the intellectual abilities of children between the ages of 6 and 16 years and 11 months.[18] It offers a comprehensive assessment, including an overall measure of intellectual functioning referred to as the Full-Scale Intelligence Quotient (FSIQ).

The Korea Internet Addiction Scale (K-Scale)

The K-Scale is a self-report questionnaire used to measure an individual's tendency toward Internet addiction. The original 40-item version was subsequently condensed to create a 20-item short form. This Likert-type scale provides response options ranging from 1 ("never") to 4 ("always"), resulting in total scores between 20 and 80. The short form of the K-Scale, as employed in this study, demonstrated excellent internal consistency with Cronbach's alpha values of 0.89 for elementary school students and 0.91 for middle school students.[19]

Advanced Test of Attention (ATA)

The Advanced Test of Attention (ATA), developed by Hong et al, serves as an assessment tool for children aged 5 and above, focusing on their sustained and selective attention capabilities and impulse control.[20] This instrument aids in distinguishing children with attention-related disorders, such as ADHD. The ATA comprises both visual and auditory tasks, where a combination of target and non-target stimuli is presented at regular intervals. Participants are instructed to exclusively respond to the target stimuli, utilizing either a keyboard or a mouse. The evaluation encompasses various variables, including omission errors for assessing attention lapses, commission errors to gauge impulsivity, response time for evaluating information processing speed, and the standard deviation of response time to measure consistency in attentional concentration.

Kiddie Schedule for Affective Disorders and Schizophrenia Present and Lifetime Version (K-SADS-PL)

The K-SADS-PL, originated by Kaufman et al, constitutes a semi-structured interview framework devised to evaluate both present and past diagnostic conditions encompassing 32 psychiatric disorders prevalent in children and adolescents, alongside the assessment of symptom severity adhering to DSM-IV diagnostic criteria.[21] A Korean rendition of the K-SADS-PL was translated and validated for its reliability and validity by Kim et al, demonstrating its effectiveness in diagnosing disorders such as ADHD, tic disorders, oppositional defiant disorder, depressive disorders, and anxiety disorders.[22]

Korean ADHD Rating Scale (K-ARS)

The ADHD Rating Scale (ARS), devised by DuPaul, serves as a behavioral evaluation instrument tailored for the assessment of ADHD manifestations among school-aged children.[23] Comprising 18 items in accordance with the DSM-IV diagnostic criteria for ADHD, the scale delineates inattention symptoms through odd-numbered items and hyperactivity-impulsivity symptoms through even-numbered items. Translated by So et al, the K-ARS has exhibited commendable reliability and validity.[24]

Stroop Test

The Stroop Test functions as a measure utilized to appraise the efficacy of inhibitory processes localized within the frontal lobe. Comprising three distinct conditions, it encompasses the Word score, evaluating rapid word reading within a designated 45-second timeframe; the Color score, assessing prompt color naming of color patches; and the Color-Word score, scrutinizing the capacity to suppress automatic responses and instead articulate the ink color when confronted with

incongruent word-color pairs. Standardization of the Korean iteration of the Stroop test was undertaken by Shin and Park.[25]

Children's Color Trails Test (CCTT)

The Cognitive Clock Test (CCTT) assesses frontal lobe-associated functions, including visual-motor coordination, attention, visual scanning, and cognitive flexibility. It is structured into two components: CCTT-1, which entails linking numbers sequentially (eg, 1-2-3), and CCTT-2, wherein participants must connect numbers while alternating colors (eg, Pink1-Yellow2-Pink3). The Korean adaptation of this assessment was formulated by Koo and Shin.[26]

Statistical Analysis

Demographic characteristics within each group were scrutinized using independent *t*-tests and a chi-square test. To compare clinical variables between the two groups (active MNF vs sham) before and after the intervention, we conducted a repeated-measure analysis of variance (ANOVA). We considered statistical significance to be present when $p<0.05$ and performed all data analyses using the Statistical Package for the Social Sciences (SPSS) software, version 25.0 (SPSS Inc., Chicago, IL, USA).

Result

Demographic Characteristics

This study included a total of 61 participants (mean [SD] age, 11.24 [1.84] years; 30 male participants [49.2%]). No significant differences in the sex ratio, age, and Full-Scale Intelligence Quotient (FSIQ) were found between the MNF group and sham group (Table 1). To compare baseline values between the sham and MNF groups, we conducted an independent samples *t*-test on the test results and have included the findings in Tables S1 and S2.

Comparisons of the Means of Parents' Self-Scale Variables

In the case of K-ARS scores, there was a significant main effect of group (p=0.027), and a significant main effect of time (p=0.002). However, the interaction effect was not significant. For BAI and WURS scores, significant main effect of time was observed, but there were no significant main effects or interaction effects between the groups. Additionally, for other self-report scales completed by parents, there were no significant changes related to the use of mobile neurofeedback (Table 2).

Comparisons of the Means of Children's Self-Scale Variables

While the main effect of group on K-Scale scores was not significant, there was a significant main effect of time (F=7.595, p=0.008). Furthermore, a significant interaction effect between the group and time (F=5.979, p=0.017) was observed. In contrast, there were no significant changes associated with the use of mobile neurofeedback in other self-report measures completed by children. (Table 3).

Table 1 Demographic Characteristics of Neurotypical Children

	Neurotypical		
M(SD)	**MNF (n=31)**	**Sham (n=30)**	**p**
Age	10.61 (1.80)	10.93 (1.84)	0.494
Sex (n)			0.900
Male	15 (48%)	15 (50%)	
Female	16 (52%)	15 (50%)	
FSIQ	95.39 (15.87)	96.20 (12.21)	0.824

Note: Data are mean (SD), n (%).
Abbreviations: M, mean; SD, standard deviation; MNF, Mobile neurofeedback; FSIQ, Full-Scale Intelligence Quotient.

Table 2 Comparisons of the Means of Parents' Self-Scale Variables Between MNF and Sham Groups

M(SD)	MNF (N=31)		Sham (N=30)		F(Group)	F(Time)	F(g X t)
	Pre	Post	Pre	Post			
BDI-II	9.48(6.54)	7.32(5.90)	9.93(9.00)	6.90(6.57)	0.000	9.485	0.267
BAI	4.52(5.89)	3.90(4.06)	3.97(4.58)	4.07(8.27)	0.020	0.163**	0.314
BIS	24.55(8.04)	23.23(7.85)	20.27(7.62)	20.87(7.16)	3.293	0.251	1.780
K-ARS	7.68(6.00)	4.32(5.81)	4.13(3.68)	3.10(3.33)	5.178*	10.359**	2.899
DBDS	2.16(3.59)	2.19(3.28)	1.57(2.06)	1.90(2.59)	0.555	0.155	0.105
ETI	1.65(2.24)	3.16(5.80)	2.33(3.29)	2.60(4.58)	0.006	1.515	0.744
YGTSS	0.06(0.36)	0.00(0.00)	0.20(0.93)	0.10(0.55)	1.183	0.747	0.035
WURS	40.26(15.286)	38.42(11.06)	39.80(16.85)	37.53(13.06)	0.037	4.374*	0.048

Note: *p<0.05, **p<0.01.
Abbreviations: MNF, Mobile neurofeedback; M, mean; SD, standard deviation; BDI-II, Beck Depression Inventory-II; BAI, Beck Anxiety Inventory; BIS, Barratt Impulsiveness Scale; K-ARS, Korean ADHD Rating Scale; DBDS, Disruptive Behavioral Disorder Scale; ETI, Early Trauma Inventory; YGTSS, Yale Global Tic Severity Scale; WURS, Wender Utah Rating Scale.

Table 3 Comparisons of the Means of Children's Self-Scale Variables Between MNF and Sham Groups

M(SD)	MNF (N=31)		Sham (N=30)		F(Group)	F(Time)	F(g X t)
	Pre	Post	Pre	Post			
CDI	7.77(5.64)	6.52(6.29)	6.80(4.75)	6.87(6.25)	0.058	0.709	0.876
BIS	28.23(9.87)	27.97(11.04)	28.47(8.24)	27.73(8.63)	0.000	0.358	0.082
STAI-T	29.58(7.66)	28.29(7.74)	26.27(7.22)	26.23(5.68)	2.673	0.685	0.618
STAI-S	30.94(6.18)	29.39(6.29)	30.07(6.55)	30.13(6.33)	0.002	0.826	0.981
SCARED	14.77(10.10)	11.03(9.87)	10.27(6.74)	10.23(10.72)	1.574	2.486	2.399
K-scale	56.13(15.34)	50.55(17.94)	53.17(12.04)	52.83(11.81)	0.009	7.595**	5.979*

Note: *p<0.05, **p<0.01.
Abbreviations: MNF, Mobile neurofeedback; M, mean; SD, standard deviation; CDI, Children's Depression Inventory; BIS, Barratt Impulsiveness Scale; STAI, The State-Trait Anxiety Inventory; SCARED, The Screen for Child Anxiety Related Emotional Disorders; K-scale, the Korea Internet addiction scale.

Comparisons of the Means of Children's K-WISC-IV, Stroop, ATA, CCTT Variables

While the main effects of group and time were not significant for K-WISC IV working memory, a significant interaction effect between group and time was observed (F=5.102, p=0.028). For ATA visual response time, the main effect of group was not significant, but there was a significant main effect of time (F=12.259, p=0.001), and a significant interaction effect between group and time (F=4.727, p=0.034). In the case of ATA auditory commission error, the main effect of group was significant (F=4.594, p=0.030), and there was also a significant main effect within time (F=20.981, p<0.001). An interaction effect between group and within-group factors was also significant (F=11.053, p=0.002). These three measures collectively suggest that in comparison to the MNF group, the sham group exhibited an improvement in performance (Table 4).

Table 4 Comparisons of the Means of Children's K-WISC-IV, Stroop, ATA, CCTT Variables Between MNF and Sham Groups

M(SD)	MNF (N=31)		Sham (N=30)		F(Group)	F(Time)	F(g X t)
	Pre	Post	Pre	Post			
K-WISC-IV							
FSIQ	96.32(14.19)	100.39(14.51)	95.23(14.17)	104.77(13.34)	0.258	18.568***	3.003
VCI	94.13(13.35)	97.19(12.44)	93.20(14.29)	99.10(13.96)	0.030	4.845*	0.485
PRI	103.10(15.22)	109.48(16.00)	102.27(14.44)	110.20(17.28)	0.000	13.689***	0.160
WMI	97.87(16.98)	96.94(16.80)	94.87(15.46)	102.13(15.43)	0.087	3.040	5.102*
PSI	90.94(20.83)	97.03(14.15)	96.47(17.33)	103.20(14.41)	2.457	8.508**	0.021

(*Continued*)

Table 4 (Continued).

M(SD)	MNF (N=31)		Sham (N=30)		F(Group)	F(Time)	F(g X t)
	Pre	Post	Pre	Post			
Stroop							
Word	75.74(18.49)	84.29(14.29)	77.93(20.62)	86.47(15.03)	0.313	16.772***	0.000
Color	60.90(15.00)	69.03(17.29)	65.07(18.98)	74.60(19.52)	1.282	35.169***	0.222
Color-Word	39.16(15.12)	45.84(15.38)	43.20(19.00)	52.80(20.63)	1.642	32.819***	1.058
Interference score	21.74(7.94)	23.19(8.62)	21.87(9.57)	21.80(11.18)	0.098	0.288	0.346
ATA visual[#]							
Omission error	63.35(21.13)	65.90(20.87)	62.10(20.90)	65.63(23.02)	0.027	1.044	0.027
Commission error	72.39(22.70)	69.35(20.17)	63.00(16.83)	56.77(17.11)	6.184**	4.206**	0.502
Response time	58.94(9.76)	67.77(13.56)	66.50(12.86)	68.57(12.58)	2.345	12.259**	4.727*
SD of response time	64.71(23.07)	70.39(22.84)	60.23(19.07)	65.00(20.51)	1.080	3.544	0.027
ATA auditory[#]							
Omission error	65.32(19.96)	69.48(23.25)	61.10(18.68)	63.97(21.83)	0.978	2.621	0.089
Commission error	71.00(21.11)	68.87(22.07)	66.43(19.20)	53.03(12.18)	4.954*	20.981***	11.053**
Response time	45.68(13.41)	49.81(13.30)	50.33(9.74)	53.03(9.89)	1.998	9.136**	0.400
SD of response time	50.19(10.40)	51.74(10.50)	46.97(9.13)	45.00(9.76)	5.140*	0.026	1.831
CCTT							
CCTT-1	21.58(9.23)	18.29(7.02)	21.83(8.65)	17.53(6.06)	0.021	15.257***	0.270
CCTT-2	43.29(15.84)	36.42(10.20)	44.87(18.22)	36.57(12.99)	0.061	31.152***	0.276

Note: *p<0.05, **p<0.01, ***p<0.001.
Abbreviations: M, mean; SD, standard deviation; K-WISC-IV, Korean Wechsler Intelligence Scale for Children-Fourth Edition; ATA, Advanced Test of Attention; CCTT, Children's Color Trails Test; MNF, Mobile neurofeedback; FSIQ, full scale intelligence quotient; VCI, verbal comprehension index; PRI, perceptual reasoning index; WMI, working memory index; PSI, processing speed index.

Discussion

This study evaluated the effects of mobile neurofeedback on internet addiction in typically developing children through a double-blind, sham-controlled randomized clinical trial. Active mobile neurofeedback demonstrated significant improvements in children's K-scale scores compared to the sham control group. These results suggest the potential positive impact of mobile neurofeedback on internet addiction in children. However, aside from the enhanced scores on the K-scale, other self-report measures completed by the children and parents, intelligence tests, attention tests, and evaluations of cognitive function did not show improved outcomes.

The primary finding of this study reveals a significant improvement in children's K-Scale scores when comparing the MNF group with the sham group. Prior to the development of the K-Scale in Korea, many studies utilized Young's Internet Addiction Test. However, there was an issue of overdiagnosing internet addiction risk groups in the general population, ranging from 10–20%, before the K-Scale was established. To effectively identify individuals at risk of addiction, the K-Scale was developed by encompassing sub-scales measuring core addiction symptoms and contributing/direct factors.[27] Among the children participating in this study, the mean K-Scale scores were 56.13 (±15.34) for the MNF group and 53.17 (±12.04) for the Sham control group. The K-Scale's cut-off value identifies a potential risk group between 41 and 45 points, while scores of 46 or above denote a high-risk group.[28] Therefore, all children participating in this study (MNF group and Sham control group) fall within the high-risk group category. Although no other psychopathologies were observed during the initial assessment, it was anticipated that children with high internet dependency participated, hence the significant improvement in the degree of internet addiction was confirmed through mobile neurofeedback intervention.

Furthermore, in this study, the potential improvement of internet addiction through mobile neurofeedback suggests the internal regulation of dopaminergic midbrain activity.[29] The substantia nigra (SN) and ventral tegmental area (VTA), primarily dopaminergic midbrain regions, are highly implicated in reinforcement learning, motivation, and decision-making, often associated with psychiatric disorders and addiction. The SN/VTA complex comprises the highest concentration of dopaminergic neurons in the human brain.[30] Neural activity in these areas is linked to dopamine release and is known to be the origin of the mesolimbic, mesocortical dopamine pathways, involving the ventral tegmental area, substantia nigra pars compacta, and their projections.[31] When unexpected rewards occur, dopamine neurons shaping the origin of the mesolimbic and mesocortical pathways are activated. Activities such as internet engagement and gaming, often favored by children, can serve this role. A study investigating whether individuals, specifically young, healthy volunteers, could self-regulate SN/VTA activity through imagining pleasant scenes and whether neurofeedback could aid in this process was conducted. Participants receiving actual feedback on SN/VTA activation through online neurofeedback showed enhanced abilities in upregulating SN/VTA and concurrent activation in other dopaminergic regions. Additionally, they exhibited increased connectivity along the substantia nigra pathway compared to the control group.[32] Therefore, it is presumed that the children participating in this study received neurofeedback information while engaging in gaming activities, allowing them to self-regulate SN/VTA activity. This regulatory enhancement potentially contributed to reduced immersion in activities such as gaming and internet engagement.

On the other hand, active mobile neurofeedback did not yield superior results compared to the sham control group in other self-report scales and cognitive function evaluations. While the outcomes of this study were negative, recent research on neurofeedback training for cognitive enhancement in healthy subjects is actively progressing. Various research regarding the use of neurofeedback as a tool to improve cognition besides rehabilitation in healthy young adults, older adults, athletes, and the elderly was reported.[33] Specifically, neurofeedback training has demonstrated substantial efficacy in augmenting working memory (WM), mood regulation, and improving sleep quality among participants.[34,35] Additionally, it has shown a medium to large effect on enhancing executive functions and a generally moderate effect size, exhibiting a broad spectrum from low to substantial impact on attentional mechanisms. However, while many studies have presented promising outcomes, not all have observed significant alterations in EEG signals directly correlating with changes in behavioral performance.[36] This discrepancy suggests that the relationship between changes in brain activity induced by neurofeedback and consequent behavioural modifications in healthy individuals remains somewhat inconclusive. In our study, we also observed no significant improvements in other self-report measures and cognitive function tests besides K-scale scores. This may be attributed to the short intervention period of three months, but it is possible that even with a longer intervention period, there may be limited benefits for healthy subjects. Therefore, additional research is needed to determine whether changes in brain activity caused by neurofeedback lead to changes in behaviour and performance in healthy individuals.

This study recognizes several constraints that warrant careful consideration when interpreting the research outcomes. Firstly, the study was limited by a small sample size, potentially compromising the generalizability and robustness of the findings. Secondly, the treatment duration was relatively brief, with the post-assessment conducted only three months after the intervention, possibly insufficient to fully capture the comprehensive effects of the treatment. Extending the duration of the intervention and incorporating more prolonged follow-up assessments could offer a more thorough insight into the intervention's efficacy and its enduring impact on cognitive performance. Furthermore, a limitation of our study is the omission of key variables related to the neurocognition of children, such as parental education, household income, and the quality of home environment. Lastly, owing to minimal alterations in the clinical variables, the study did not adequately explore the relationship between electrophysiological changes and the improvement of cognition. Further investigations with a focus on elucidating the association between changes in electrophysiological markers and enhancements in cognitive function would contribute substantially to comprehending the mechanistic underpinnings of the intervention's effects.

Conclusion

The comparison between the MNF group and the sham group revealed a significant improvement in scores on the Korean Internet Addiction Self-Diagnostic Scale among children. These findings suggest that the use of mobile neurofeedback

can lead to a meaningful reduction in internet usage among typically developing children. However, the MNF group did not demonstrate superior effectiveness compared to the sham group in other self-report scales for children and parental reports and cognitive function. Given that the study participants were typically developing children rather than those diagnosed with ADHD, differences in effectiveness compared to patient populations are possible. Additionally, it is possible that a short-term intervention of 3 months was not sufficient to induce change. Therefore, it is necessary to confirm through intervention of more than 3 months.

Data Sharing Statement

The datasets generated or analyzed during the study are available from the corresponding author on reasonable request.

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Disclosure

The authors report no conflicts of interest in this work.

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