CYBERPSYCHOLOGY & BEHAVIOR
Volume 7, Number 5, 2004

Neurofeedback Training with Virtual Reality for Inattention and Impulsiveness

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ABSTRACT

In this research, the effectiveness of neurofeedback, along with virtual reality (VR), in reducing the level of inattention and impulsiveness was investigated. Twenty-eight male participants, aged 14–18, with social problems, took part in this study. They were separated into three groups: a control group, a VR group, and a non-VR group. The VR and non-VR groups underwent eight sessions of neurofeedback training over 2 weeks, while the control group just waited during the same period. The VR group used a head-mounted display (HMD) and a head tracker, which let them look around the virtual world. Conversely, the non-VR group used only a computer monitor with a fixed viewpoint. All participants performed a continuous performance task (CPT) before and after the complete training session. The results showed that both the VR and non-VR groups achieved better scores in the CPT after the training session, while the control group showed no significant difference. Compared with the other groups, the VR group presented a tendency to get better results, suggesting that immersive VR is applicable to neurofeedback for the rehabilitation of inattention and impulsiveness.

INTRODUCTION

ATTENTION is the cognitive ability of information management and is positively required for learning, information acquirement, and the social adaptation of children.[1–7] Individuals with short attention spans cannot effectively or selectively acquire information and subsequently lack in competitiveness and in the ability to adapt socially. Moreover, hyperactivity, emotional disturbance, or low self-esteem can also occur in these individuals. Attention problems not only lead to learning problems, but also affect social and personal relationships.[8–9]

Impulsiveness is an additional characteristic of an attention deficit, which deepens the problem. Impulsive children and adolescents have difficulties in thinking or behavioral control. Finally, their inconsiderate behavior makes other people angry, which also provokes social adaptation problems.[10]

As mentioned above, inattention and impulsiveness interact with the home, educational, and social environments, and they induce many secondary problems in cognition, behavior, and social adaptation. These problems sometimes co-exist in attention deficit hyperactivity disorder (ADHD), learning disorder, conduct disorder, emotional disorder, and oppositional defiant disorder.[11–13]

From the results of previous research, the arousal level of an individual has been found to be an important key.[14–20] An extremely low or high arousal level indicates possible inattention or impulsiveness. It is therefore necessary to maintain an optimum level of arousal for the control of attention and impulsiveness.

There has been much research on controlling the arousal level. In clinical settings, behavioral therapy, medicine, or combinations of the two have been used to try to deal with the arousal level.[21]

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However, these treatment methods can have many problems, such as high cost and complicated treatment procedure, or side effects, including insomnia, dizziness, tiredness, and so on. Moreover, the interruption of treatment could cause a rapid decrease in the remedial value.[22] To increase the arousal level and maintain the treatment efficacy, cognitive training, cognitive behavior training, and neurofeedback have been applied.

Recently, the application of virtual reality (VR) to cognitive training, especially in assessing attention and rehabilitation, has been verified by studies showing that VR can be used as an alternative tool for assessing attention and rehabilitation.[23] In a previous study, we developed a cognitive training program with immersive VR and performed a clinical trial. The study concluded that the virtual environment (VE) for cognitive training was effective in improving the attention span of children and adolescents with behavioral problems, helping them to learn to focus on some tasks more than the existing cognitive training.[24]

Over the last few decades, electroencephalography (EEG) has been applied in the possible diagnostic assessment and treatment of people with attention or behavioral problems.[25,26] Many studies on neurofeedback, or EEG biofeedback, have reported promising results, not only in significant reductions of hyperactive, inattentive, and disruptive behaviors, but also improvements in cognitive performance and IQ scores.[27–31] The neurofeedback method enables participants to recognize their own brain condition through real-time EEG signal processing and allows them to try to control the mental condition by themselves. These studies emphasized that reinforcement of the beta wave showed good results in treating participants with attention problems.

The effects of neurofeedback can vary as an operational method and procedure. An earlier neurofeedback method presented just the EEG signal to participants, but later researchers have proposed the use of computer programs that have shown better performance.[28]

To obtain a notable effect with neurofeedback, Cartozzo et al. proposed two or three sessions per week (50 min for each session), with a total of 40 sessions.[32] They also reported that, for the first significant improvement to emerge, at least 10 sessions were required. This means that longer sessions of neurofeedback treatment could make patients bored and tired, and even result in a high cost. In this paper, considering the above factors, an effective method of neurofeedback, combined with VR, for the rehabilitation of children with attention problems and impulsiveness is proposed.

MATERIALS AND METHODS

Participants

Twenty-eight male participants, aged 14–18, who had committed crimes and had been isolated in a reformatory participated in this study. Although they were not officially diagnosed as having ADHD, they had some difficulty in learning and were inattentive, impulsive, hyperactive, and distracted. Participants were randomly assigned to one of three groups: the control group (n = 9), the VR group (n = 10) or the non-VR group (n = 9).

Virtual classroom

A virtual classroom was created in a previous study that made children and adolescents feel intimate.[23] This virtual classroom was also used in the present study. The user was able to look around the virtual world with a head-mounted display (HMD; Daeyang E&C, virtual image size was 44 in at 2 m and viewing angle was 62 degree diagonal) and a head tracker (InterTrax II, 3 degrees of freedom). In this virtual classroom, the participants performed neurofeedback training.

Neurofeedback

Scalp potentials were recorded at the placement of Cz using silver cup electrodes grounded at the right and left ears. For signal acquisition, a four-channel EEG measurement device (LAXTHA Inc.) with a sampling rate of 256 Hz was used.

For real-time analysis, a 768-sample data block was chosen. Figure 1 shows the processing block

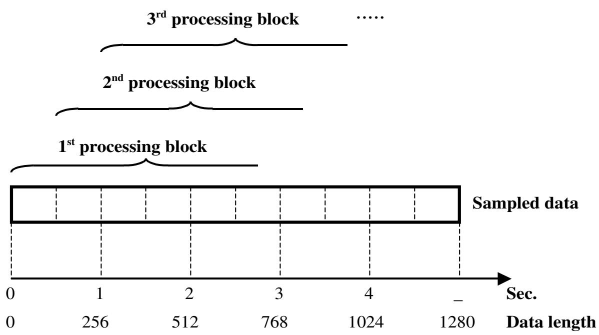

FIG. 1. The processing block. A 768-sample processing block was updated every 0.5 sec.

was updated every 0.5 sec; thus, feedback parameters could be obtained every 0.5 sec. Before the EEG signal could be analyzed, it had to be preprocessed by a 60-Hz notch filter and a low-pass filter, with a cutoff frequency of 50 Hz.

When the signal-to-noise ratio (SNR) is low and the length of the desired signal short, traditional analysis methods of power spectral density (PSD) may not provide accurate results. Fast Fourier Transform (FFT), a well-known method, provides poor frequency resolution, which may render the spectral responses of two or more signals, with short length and low SNR, indistinguishable. Another important limitation of FFT is that the windowing process causes spectral leakage in the frequency domain.

To overcome these limitations, an autoregressive (AR) method, using the adaptive least-mean-square (LMS) algorithm, was applied to estimate the PSD.[33] The AR method is the most popular of the parametric methods for acquiring the PSD, which is calculated as follows:

$$S_{AR}(\omega) = \frac{\sigma_e^2}{|1 + a_1(n)e^{-j\omega\Delta t} + \ldots + a_M(n)e^{-jM\omega\Delta t}|^2}$$

where a^m represents the AR coefficients at the mth stage, M the AR model order, and Δt the sampling interval with $\sigma^2{}_e$ assumed to be constant. Because the block AR methods may not track slow changes in the spectra of non-stationary signals, as is the case for biomedical signals, the coefficients were estimated adaptively for each sample, using the LMS algorithm.

The wave parameters, such as delta (0.5–3 Hz), theta (4–7 Hz), alpha (8–12 Hz), sensorimotor rhythm (SMR) (12–15 Hz), and beta (15–18 Hz), were analyzed by averaging each spectral component.

Since the beta wave ratio of the brain signal is closely related to attention and impulsiveness, as mentioned above, participants were encouraged to reinforce the wave ratio. When the beta wave ratio of the participant's EEG signal was greater than the baseline threshold, the participants would earn a score for a positive reinforcement outcome in the VE.

As the scores progressed, a dinosaur's egg rose from the desk, which then splits in two. From the broken egg, each part of a dinosaur picture puzzle gradually appeared on the whiteboard, which finally completed the puzzle. If the score reached "100," and all six parts of the picture had been put together, the participant would hear the dinosaur roar (Fig. 2).

Experimental procedure

All participants performed a continuous performance task (CPT) before and after the complete training session. A CPT provides measurements of the ability to respond and pay attention. In a CPT, the participants must respond to the target stimuli (characters except "X"). Time intervals between stimuli ranged from 1 to 4 sec, with an exposure time of 250 msec. The measurements in the CPT were as follows: the number of hits, reaction times, the perceptual sensitivity, omission and commission error, and the response bias.

The VR and non-VR groups underwent eight sessions over a 2-week period, with each session taking approximately 20 min. The control group performed no training session during this period.

All the participants in the VR group were trained to become accustomed to the VE, first by using a 1-minute warm-up. Before every training session, the baseline threshold for the beta wave ratio was calculated by measuring 2-min EEG signals with the eyes open, because different emotional and physi-

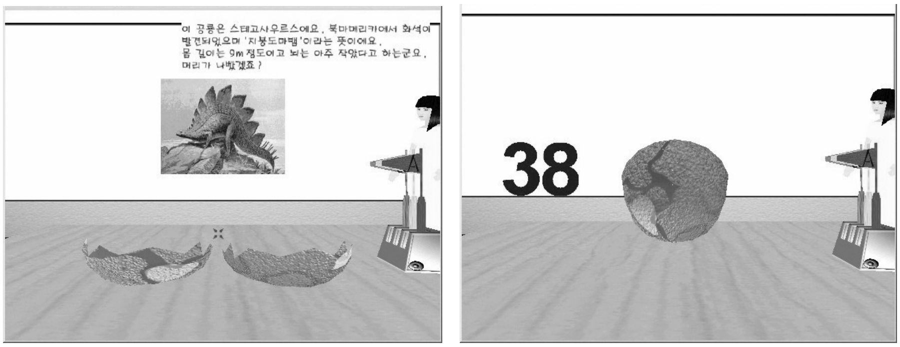

FIG. 2. Scenes of neurofeedback training.

cal condition can occur on a daily basis. While the VR group used a HMD and a head tracker in each session, the non-VR group used only a computer monitor. Accordingly, only the VR group was able to look around the virtual classroom. With this exception, the two groups performed the same neurofeedback training tasks. During the VR neurofeedback and non-VR neurofeedback training, the task completion time and the beta wave ratio were measured. During the experiment, participants sat in a comfortable chair in a silent dark room.

A three (VR group/non-VR group/control group: between-subject variable) by two (pre/post training: within-subject variable) analysis of variance (ANOVA) test with repeated measures was used to evaluate the effects of the tasks.

RESULTS

The mean pre- and post-training CPT scores, and standard deviation of each score are presented in Table 2.

Number of hits in CPT

The ANOVA test showed that the main effect for the measurement time ($F(1,25) = 39.775$, $p < 0.01$) and the interaction effect of group × the measurement time ($F(2,25) = 8.715$, $p < 0.01$) were significant. Figure 3 shows the number of hits of the VR group rapidly increased compared to those of the non-VR and control groups at the completion of all of the training sessions.

Reaction time in CPT

There was a significant main effect for the measurement time ($F(1,25) = 8.545$, $p < 0.01$), whereas the interaction effect of group × the measurement time ($F(2,25) = 3.178$, $p = 0.059$) was marginally significant.

Perceptual sensitivity in CPT

The main effect of the measurement time was significant ($F(1,25) = 12.905$, $p < 0.01$).

Omission error in CPT

The same tendency was observed with the number of hits. That is, the main effect for measurement time ($F(1,25) = 31.179$, $p < 0.01$) and the interaction effect of a group × the measurement time ($F(2,25) = 7.273$, $p < 0.01$) were significant. Figure 4 shows that omission errors for the VR group decreased further than those for the non-VR and control groups.

TABLE 1. MEAN CPT SCORES AND STANDARD DEVIATIONS (SD) OF EACH GROUP

Measurements	*Group*	*Pre-training score M(SD)*	*Post-training score M(SD)*
Attention			
Number of hits	VR	310.78 (5.02)	322.22 (1.56)
	Non-VR	311.40 (3.69)	319.30 (1.89)
	Control	314.78 (5.47)	315.44 (4.45)
Reaction time (T-score)	VR	54.52 (15.72)	38.62 (19.80)
	Non-VR	49.50 (14.32)	48.85 (17.30)
	Control	52.71 (17.85)	47.16 (22.88)
Perceptual sensitivity (T-score)	VR	55.35 (8.30)	41.83 (7.70)
	Non-VR	55.62 (10.52)	49.77 (17.19)
	Control	53.33 (5.52)	50.52 (10.77)
Omission error	VR	13.22 (5.02)	1.89 (1.62)
	Non-VR	11.60 (4.77)	4.70 (1.89)
	Control	9.22 (5.47)	8.56 (4.45)
Impulsivity			
Commission error	VR	19.44 (7.67)	12.67 (10.33)
	Non-VR	17.10 (9.97)	16.30 (11.12)
	Control	19.11 (7.77)	15.11 (10.47)
Response bias (T-score)	VR	56.94 (8.45)	66.74 (22.30)
	Non-VR	57.01 (9.79)	64.54 (21.78)
	Control	49.88 (5.50)	59.41 (14.63)

TABLE 2. STATISTICAL RESULTS FOR THE AVERAGE RATIO OF THE BETA WAVE IN NEUROFEEDBACK TRAINING

Source	*Type III sum of squares*	*df*	*Mean square*	*F*	*Significance*
Group	6.635E-08	1	5.635E-08	10.392	0.005[a]
Error	8.675E-08	16	5.422E-09		
Factor	3.805E-08	1	3.805E-08	14.125	0.002[a]
Factor*Group	2.139E-09	1	2.139E-09	0.794	0.386
Error (factor)	4.310E-08	16	2.694E-09		

[a]$p < 0.01$.

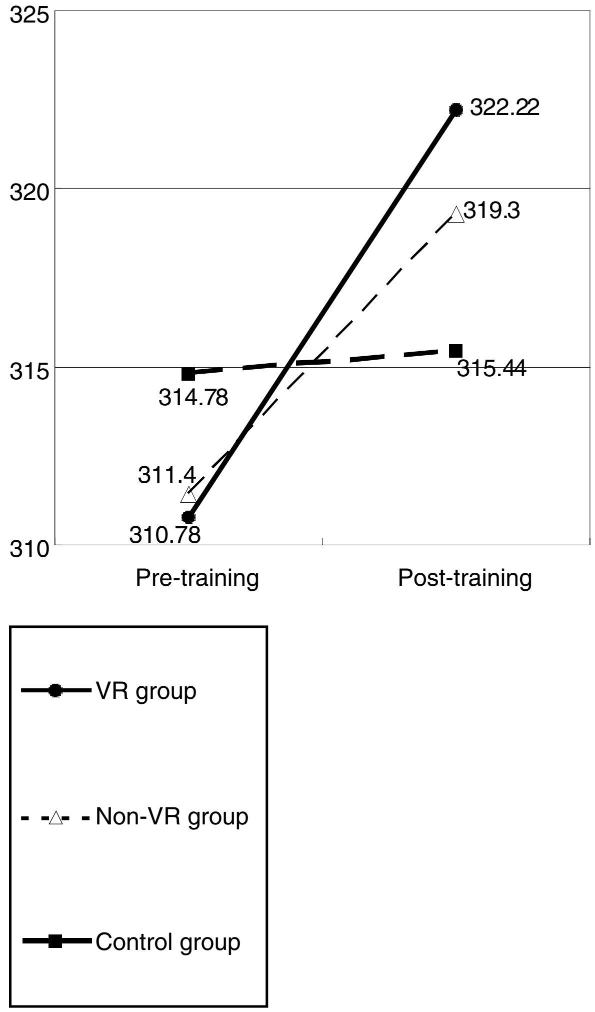

FIG. 3. The mean number of hits in CPT. The number of hits of the VR group increased much more than those of the other groups after training, with a significant interaction effect between the training group and the measurement time.

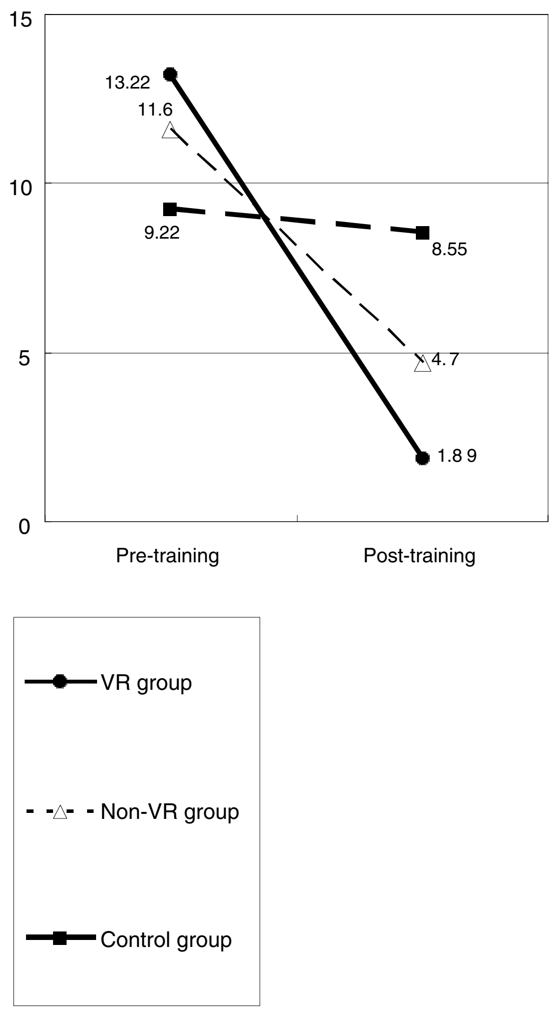

FIG. 4. The mean omission error in CPT. The omission error of the VR group decreased more rapidly than that of the other groups after training, and the interaction effect between training group and measurement time was significant.

Commission error and response bias in CPT

The main effect of the measurement time on commission errors ($F(1,25) = 5.698$, $p < 0.05$) and response bias ($F(1,25) = 7.724$, $p < 0.01$) were significant.

Mean beta wave ratio of EEG signal in neurofeedback training

Table 2 shows that the main effects of group ($F(1,16) = 10.392$, $p < 0.01$) and time ($F(1,16) = 14.125$, $p < 0.01$) were significant. As shown in Figure 5, the VR group always had higher rates than the non-VR group, with the exception of the fourth session.

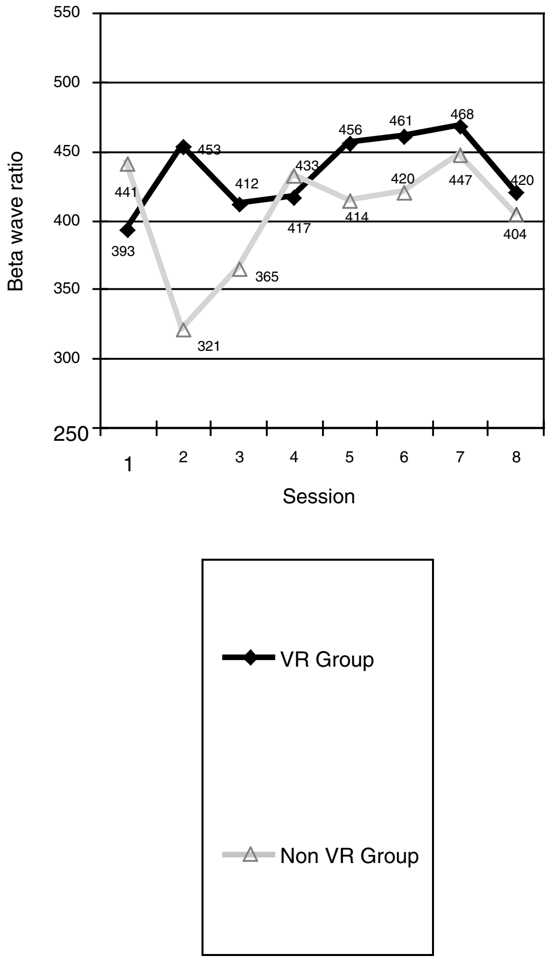

FIG. 5. The mean beta wave ratio in neurofeedback training. The VR group had a greater beta wave ratio than the non-VR group in almost every session.

Mean task completion time in neurofeedback training

Table 3 shows that the main effect of time was statistically significant ($F(1,15) = 5.658$, $p < 0.05$). Despite this, Figure 6 shows that the completion time of the VR group decreased more steeply than that of the non-VR group after the second session.

DISCUSSION

The main goal of this study was to verify the effect of applying VR to neurofeedback in the assessment and rehabilitation of inattention and impulsiveness.

Compared to the control group, both the VR and non-VR groups earned higher scores in the number of hits with the CPT, and fewer omission errors after completing a training session. Perceptual sensitivity represents the ability to distinguish target stimuli from other stimuli, and is related to selective attention. When the T score of this measurement is over 60, a deficit in selective attention is implied. For our experiments, all groups earned lower T scores for perceptual sensitivity after training, with the VR group showing much lower scores than the other groups, although this difference was not statistically significant. The reaction time for the CPT is an indicator that measures the velocity of the motor reaction or information management, and is sensitive to differences in the sustained attention abilities of a subject. The results showed a significant decrease in the reaction time of the VR group after training, implying they paid more attention to the tasks and made their decisions more rapidly. These results suggest that neurofeedback training with immersive VR is helpful in attention enhancement.

With regard to impulsivity, commission errors and the response bias in the CPT were measured. The commission error, a response to the stimulus following a non-target stimulus, is assumed to represent impulsive behavior. When the T score of the response bias is under 40, the subject is apt to respond more frequently, which also reflects an impulsive character and the propensity for failure. After training, both groups showed less commission errors and earned higher T scores for the response bias. Although it was not significant, the VR group was the most improved of the three groups.

As expected, measurements of the mean beta wave ratio during the neurofeedback training and the task completion times showed consistency. The results of the VR group were generally better than those of the non-VR group.

TABLE 3. STATISTICAL RESULTS FOR AVERAGE COMPLETION TIME IN NEUROFEEDBACK TRAINING

Source	*Type III sum of squares*	*df*	*Mean square*	*F*	*Significance*
Group	7178.458	1	7178.458	0.268	0.612
Error	401707.028	15	26780.469		
Factor	179791.226	1	179791.226	5.658	0.031[a]
Factor*Group	86377.408	1	86377.408	2.718	0.120
Error (factor)	476614.602	15	31774.307		

[a] $p < 0.05$.

With these aspects, we suggest that immersive VR is applicable to neurofeedback for the assessment and rehabilitation of inattention and impulsiveness.

In fact, we performed post-hoc tests for the results of CPT and there was no significant difference between VR and non-VR groups. Despite this, the VR group presented a tendency to get better results than the non-VR group in almost all criteria. This might be because we conducted only eight sessions of experiments.

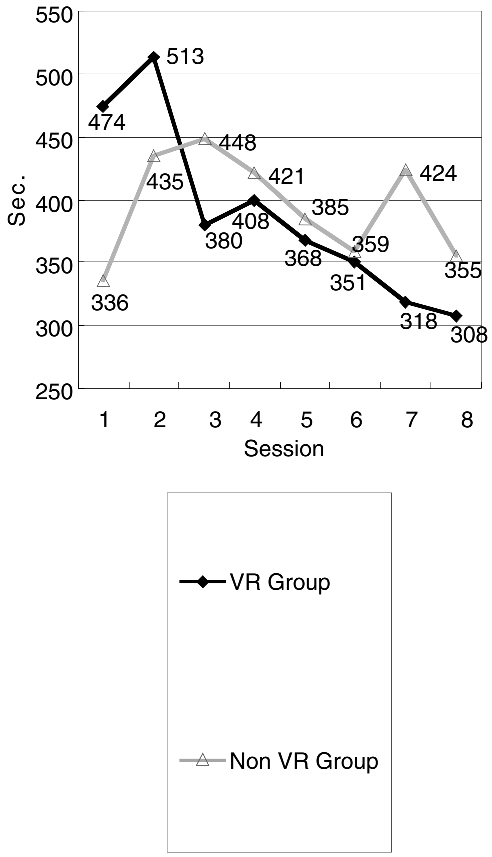

FIG. 6. The mean task completion time in neurofeedback training. From the third session, the completion time of the VR group decreases more than that of the non-VR group.

As a short period of training (2 weeks) was conducted, the long-term effect of our neurofeedback training could not be measured. Although our training methods produced some effect for a short period, more than 40 sessions may be required. There is also the need to grasp a participant's behavioral and mental characteristics, and decide the appropriate number of training sessions for each individual, in order to validate the durability of the effect.

Although only the beta wave ratio was used as a feedback control for the neurofeedback training, it brought improvements in the participants' attention and impulsivity. However, there may be a need to compare and verify other parameters, such as the alpha, theta, and SMR as adequate feedback controls.

ACKNOWLEDGMENTS

This study was supported by a grant of the Korea Health 21 R&D Project, Ministry of Health & Welfare, Republic of Korea (02-PJ3-PG6EV10–0001).

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