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RESEARCH ARTICLE

Visual Attention and Pulmonary VR Training System for Children With Attention Deficit Hyperactivity Disorder

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This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

ABSTRACT Attention deficit hyperactivity disorder (ADHD) is one of the most common behavioral disorders in children in the early school years. This study proposes a novel virtual reality (VR) training system that simultaneously improves visual attention and pulmonary function in children with ADHD using fast Pranayama breathing, which is similar to the breathing method used to measure pulmonary function. We conducted the experiment with 12 children with ADHD who have normal pulmonary function in the control group and the experimental group, using the developed visual attention and pulmonary VR training system for eight training sessions in four weeks. The proposed system for children with ADHD consists of hardware that measures breathing and three VR games that use breathing data as direct input. The experiment result was analyzed by the Paired t-test for the pre-post comparisons and the Unpaired t-test for intergroup comparisons. Based on the conducted experiments and observations, we confirmed that the developed system can simultaneously improve visual attention and breathing capacity in children with ADHD.

INDEX TERMS Input devices, virtual reality, visual attention, VR training system.

I. INTRODUCTION

Gaming experiences using virtual reality (VR) are characterized by providing users with both spatial and temporal experiences [1]. Users wearing VR devices feel like they are interacting with a virtual environment and experiencing the new world that VR enables [2]. Based on these theories, this study aims to explore how VR games can be incorporated into breathing exercises for attention training to reduce resistance to breathing exercises by making them more engaging and motivating. In VR-based education and training systems, it is crucial to apply theoretical paradigms that accurately reflect concepts and properties of cognitive functions [3], [4]. Cognitive function is divided into individual domains, such as concentration, visual perception, working memory, memory, and executive function,

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and different disorders have different profiles of cognitive function [5], [6].

Children with attention deficit hyperactivity disorder (ADHD) typically show cognitive deficits in various areas, including perceptual processing speed, attention span, working memory, visual memory, verbal memory, language comprehension, language fluency, reasoning, and problem-solving [7]. ADHD is one of the most common behavioral disorders in children [8] and is characterized by difficulty in concentrating, a short attention span, hyperactivity, and impulsivity [9], [10].

Previous studies on children with ADHD have focused on a variety of areas, including diagnosing severity [11], improving temporal cognition [12], reducing stress levels [13], and rehabilitation [14]. Of the interventions that have been studied, we were inspired by research showing that breath-focused yoga was more effective at improving attention than movement-focused yoga [15]. Pranayama breathing was significantly associated with the improvement of pulmonary function [16], [17]. Pranayama breathing helps its performers control arousal, attention, and emotions by making performers intentionally control their maximum exhalation and inhalation breath [18]. Fast Pranayama breathing is similar to the breathing required for pulmonary function tests (PFTs) used in the medical field. By repeating breathing close to the limit of breathing, such as PFT breathing or fast pranayama breathing, it is possible to train the user's breathing strength as well as the amount of breathing. In addition, previous studies showed that certain indicators of breathing, such as the peak expiratory flow rate, had a positive correlation with cognitive ability, including attention [19], [20]. However, there have been only a few research using breathing-input VR to improve attention. In our study, we tried to find out whether simultaneous improvements in attention and breathing function are possible through the VR training system.

More recently, a few researchers have explored breathing as an input to VR. One study categorized exhalations into four forms and showed VR feedback that matched the intensity and duration of the exhalation to drive engagement [21]. Another study explored pointing and selection combined with other physiological inputs, such as gaze [22].

To explore the feasibility of using breathing and VR to treat ADHD, a visual attention and pulmonary VR training system, which uses breathing as an input, was developed for children with ADHD. We implemented this VR training system using a combination of existing research and commercial training methods, including direct breathing input, VR, visual attention training, and respiratory muscle training (RMT). The previous studies showed that it was possible to observe the improvement of respiratory function by training, even if participants had ordinary respiratory functions [23], [24]. Therefore, we conducted an experiment for children with ADHD with healthy respiratory function and studied the effect of the VR training system on improving not only their respiratory functions but also their visual attention. Among the various factors of attention, we focused on visual attention, which was evaluated as having a greater severity compared to auditory attention [25]. As a medium of training, we used immersive VR games to induce the motivation of ADHD children to continue pulmonary training. The improvement in visual attention and breathing functions of children with ADHD was verified experimentally to test the following hypotheses.

Hypothesis 1: Children with ADHD can significantly improve their visual attention via training with the proposed system.

Hypothesis 2: Children with ADHD can significantly improve their pulmonary function via training with the proposed system.

To test the hypotheses above, we designed and conducted a between-subjects user experiment with children with ADHD and analyzed the data from the experiment in two ways.

The experiment was conducted with 12 children with ADHD who had healthy lungs in the control group and the experimental group. All 24 children had undergone the psychomotor program to improve attention [26]. Additionally, 12 children in the experimental group used the proposed visual attention and pulmonary VR training system for eight training sessions within four weeks. As a measure of attention, the Advanced Test of Attention (ATA) was performed [27], [28]. It measures the ability to follow instructions while being presented with a series of visual and auditory stimuli for a specific amount of time. A pre-and post-test comparison of the improvement in visual attention and pulmonary function in the experimental group was conducted. In addition, the pre- and post-test visual ATA scores of the control group were measured at four-week intervals. Next, a between-subject comparison was made with the scores of the experimental group. The contributions of this study, as derived from analyzing the experimental data, are as follows. Through VR serious games, we have developed three new VR-based breathing training games that can simultaneously improve visual attention and pulmonary function. The developed games can also significantly improve visual attention and pulmonary function.

II. RELATED WORKS

A. VR TRAINING SYSTEM FOR CHILDREN WITH ADHD

Immersive content development using VR has been pursued in the fields of education, science, architecture, engineering, and healthcare [29]. VR programs can easily control variables that are difficult to control in real life, provide appropriate interactions between variables to engage students, and support experiments that would be difficult or impossible in real life.

Gamification techniques for training in VR environments immerse participants in the game, enabling sustained training engagement and self-effort [30]. Training using gamification techniques in VR allows the users to gain a logical understanding of the training process as well as helps the observers define scenarios to solve challenges and collect data on the results of users achieving clear goals [31]. Research into VR environments has dealt with gamification cases and meta-studies, as well as guidelines for gamified training [32].

Studies have also reported VR training programs for children with ADHD that apply game elements to address the delayed development of cognitive skills; moreover, tests for listening, computation, reaction inhibition, vigilance, and working memory have been developed [11]. There have also been VR systems to train ADHD children's time perception [12], and visual and auditory attention [33]. Games combined with VR can provide a realistic time and space experience [34], [35] for children with ADHD, making them more likely to stick with the training process and providing motivation to maintain their attention [13].

B. VISUAL ATTENTION VR TRAINING SYSTEM

Attention impairment in children with ADHD is a major cognitive impairment as they experience problems with working memory despite that they don't have problems with information retrieval from long-term memory or in the ability to integrate information [36]. Problems with working memory can lead to a lack of cognitive capacity, causing difficulties with coherent navigation when performing specific tasks [37].

When it comes to working memory, children with ADHD evidently perform worse on spatial working memory than verbal working memory. Problems with visual sketchpad and phonological working memory are more pronounced [7], [38]. In particular, visuoperceptual attention in children with ADHD may be impaired due to inefficiencies in visual information-seeking strategies, resulting in impaired learning and task performance [39], [40].

VR is effective in improving visual attention in children with ADHD because it provides a realistic spatial and visual experience that is immersive [34] and supports spontaneous learning and interaction through practicing natural behaviors in VR [41].

C. VR AND PULMONARY TRAINING

Training to improve pulmonary function in VR has been conducted in sports science and medical therapy. Research has also been conducted on breathing training using pulmonary function measured in VR as a variable [42], ASD (autism spectrum disorder) diagnosis using machine learning [43], and the relationship between stress and movement-oriented and breathing-oriented yoga practice [15].

One study found that implementing breathing as a game in a VR environment significantly impacted users' sense of presence, fun, challenge, and success when interacting with the Vive controller and breathing [44].

Previous studies have either indirectly used sound waves, used chest straps to interfere with natural breathing, or used only exhalations, with limited studies utilizing both exhalations and inhalations for feedback in VR.

III. HARDWARE AND SOFTWARE IMPLEMENTATIONS

A. HARDWARE

We implemented a breathing input device for visual attention and pulmonary VR training. The breathing input device was hand-held (145 mm × 72 mm × 30 mm) and was 3D printed using polylactic acid (PLA) as material. For participant hygiene, a disposable mouthpiece was designed to be mounted on top of the pipe structure of the input device (Fig. 1a). Unlike the fully open breathing inlet at the top, the breathing outlet at the bottom reduced the amount of air that could pass through over the same amount of time, providing the right amount of resistance as the user bit and breathed into the device. To use RMT as a structure for breathing training, we tapered the passageway through which the breath passed, forcing the user to use the pulmonary muscles a little more than normal breathing. The inhalation and exhalation rates of the participant were measured by a pressure sensor (*D6F-PH5050AD3*) placed between the breathing inlet and outlet (Fig. 1b). The breathing data measured by the sensor were transmitted via Bluetooth to the VR system, which played back the VR feedback (Fig. 1c).

Since the main participants of this study were children, we used lightweight devices. A Samsung Gear VR was used to mount the Samsung Galaxy S20 smartphone running an Android OS and it delivered our VR game content to the children (Fig. 1d) [45].

The use of a relatively lightweight HMD compared to other commercially available VR devices facilitated the participants' experience of the proposed visual attention and pulmonary VR training system for children with ADHD. We limited the total duration of the VR experience to 15 min, given the potential for the participants' visual development to be impaired by displays close to their eyes.

B. SOFTWARE

Unity3D engine Version 2019.4.9f1, one of the long-term support versions, and C# language were used to develop training games for the VR training system for children with ADHD. As a development hardware, we used a PC running Windows 10 equipped with an Intel Core i7-8700k processor, 16GM RAM, and an NVIDIA GeForce RTX 2080ti graphic card. Three games were developed to provide feedback on respiratory input and improved attention in children with ADHD. The first game was the Rocket game (Fig. 2a), where the user's inhalation gathered power, and the exhalation provided feedback to keep the flight going. A rocket in the rocket game had an initial velocity that was proportional to the user's inhalation and a flight time as long as the exhalation lasted. We developed the app to make the users feel like they were

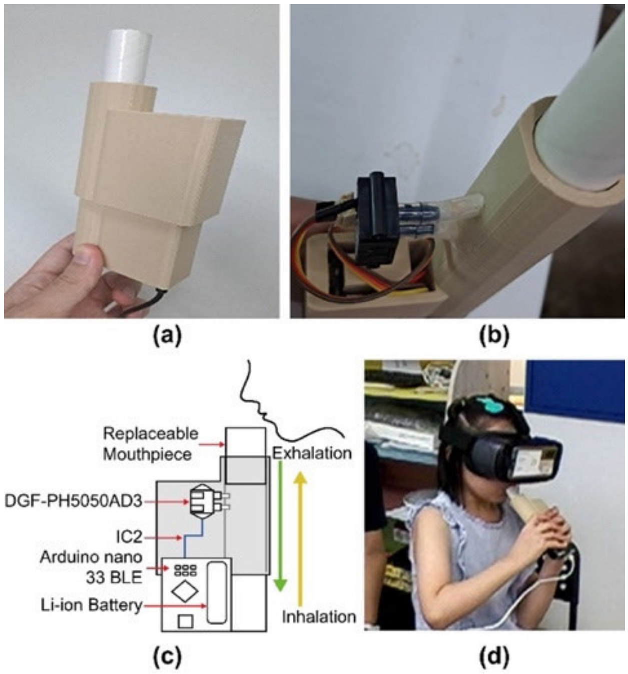

FIGURE 1. (a) 3D printed hardware using PLA material. (b) Arduino-based air pressure sensor integrated in 3D printed hardware. (c) The hardware of the visual attention and pulmonary VR training system based on the Arduino Nano 33 BLE measures the value of the pressure sensor D6F-PH5050AD3. The measured value can be transmitted through Bluetooth communication. (d) A participant wearing the Samsung Gear HMD while using the breathing input device.

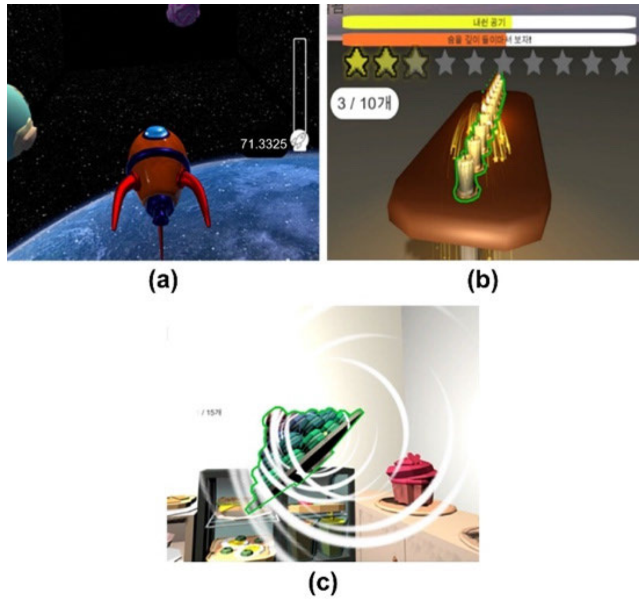

FIGURE 2. (a) Rocket game of PulmoTrainer. The goal is to fly a rocket as far as possible. (b) Candle game of PulmoTrainer. The goal is to extinguish as many candles as possible. (c) Food game of PulmoTrainer. The goal is to eat five foods per stage.

flying along with the rocket and create excitement. As an interesting visual effect, the rocket was designed to crackle as it gathered power with inhalation; moreover, it returned to its original form and started flying with exhalation. The second game was the Candle game (Fig. 2b). The users saw the flames of 10 candles in a row swaying with their breathing. The candles would blow out in proportion to the sum of the user's inhalation and exhalation volumes. When a candle was extinguished, stars burst out with a small gunpowder explosion sound to give feedback on how many candles had been extinguished. The third game was the Food game (Fig. 2c). The users were guided to look at the food and inhale. When the user's inhalation volume reached a certain level, they would be able to eat food with a swirling effect. Table 1 lists more information about the three types of games. Similar to the previous study of ADHD children's attention by Kim et al. [33], we included in our system the features to improve the user's visual attention. Users were allowed to interact only when their gaze was aligned with the object they wanted to interact with (i.e., rockets, candles, and food), and this feature affected improving visual attention.

Table 1 shows more information about the three types of games.

The Rocket and Candle games were designed to inhale and exhale the maximum amount of air as fast and hard as one could. The design was intended to encourage breathing similar to fast Pranayama breathing, leading to training in general pulmonary function. The Food game was designed to only inhale the maximum amount of air as fast and hard as one could. Unlike exhaling, which is used in daily life, such as blowing out candles, taking a deep inhaling breath is less familiar. The food game only included inhaling activities to familiarize one with the use of inhalers in cases of respiratory illness.

When the adult male breathed the most strongly, the respiratory pressure was about 330 Pa. That is, it could be estimated that the child's respiration was also in the range of −500 to 500 Pa which our respiratory sensor can measure. Therefore, we used the Pa-unit value in the game without using a separate calculation algorithm for the respiratory pressure of the child measured by our sensor.

C. TECHNICAL EVALUATION OF PULMONARY SENSING HARDWARE

A technical evaluation of the hardware was conducted to assess the objectivity of user breathing data measurement in the proposed VR training system. To observe the pressure change, we conducted three evaluations: a forward (exhalation) measurement of pressure from compressed air (BBT-001, 125W, 3L), a backward (inhalation) measurement from a vacuum pump (5Pa–0.05Mbar, 3CFM 1/4HP), and actual human breathing. A distributor delivered air equally to the hardware of our VR training system and an evaluation pressure sensor (Adafruit MPRLS, 24-bit ADC, 0–25 PSI) (Fig. 3).

TABLE 1. Details about each training game.

	Rocket game	Candle game	Food game
Type of breathing required	Inhaling as much as the users can, then exhaling as hard and as long as they can until there is no air left in their lungs		Only inhalation as much as possible at a time
Goal	Launching the rocket as far as possible The distance flown is proportional to the sum of the user's inhalation and exhalation volumes Five times in total	Blowing out as many candles as possible Up to 10 candles in a single breath Increasing by 1 breath per stage Up to 15 breaths for a total of five levels	Eating food Eating a total of 15 food items with three per stage
Structure of breathing leading to feedback	The greater the amount of inhalation and exhalation in the first second, the greater the initial acceleration of the rocket A higher volume after the first second of exhalation increases the rocket's flight distance	The higher the inhalation and exhalation volumes, the more the number of candles extinguished	The amount of inhalation accumulated during breathing is displayed It is reset when the goal is reached and food flies into the mouth
Feedback on breathing tasks	On inhalation: With more inhalation, the rocket crackles more, as if it were gathering power On exhalation: With more intense and frequent exhalations, the rocket flies higher	The candle sways with inhalation and exhalation In a single breath, for every 10% of the maximum exhalation and inhalation volume of the user's breath, one candle is extinguished	The food will fly toward the user's mouth upon taking the maximum amount of inhalation (users can try multiple times if they cannot do it in one breath)
The formula for converting breathing capacity and peak breathing pressure	For a single breath, the total amount of exhalation and inhalation is calculated by summing the breath sensor's measurement in the range of -500 to 500 Pa		
Factors to improve visual attention	It is designed to allow interaction through breathing only if users turn their heads and maintain eye contact with the object that they wish to interact with		

In the first forward evaluation, compressed air was slowly injected into the air distributor to increase the air pressure to 2,500 Pa. In the backward evaluation, the air was slowly sucked up to 2,000 Pa. Finally, for the human breathing measurements, five consecutive inhalations and exhalations were entered through a silicone tube connected to an air distributor. The values measured by the hardware of the proposed training system and the evaluation pressure sensor were simultaneously recorded on a computer (Intel i5-10300H, 16GB) via serial communication. Fig. 4 illustrates the evaluation results. In all evaluations, the hardware of the proposed training system showed high linearity with the values measured by the evaluation pressure sensors (forward: R^2 =0.989, $p<0.001$, backward: R^2 =0.996, $p<0.001$, and Human breath: R^2 =0.989, $p<0.001$). These results confirmed that the utilized hardware accurately measured the user's breathing pressure without bias.

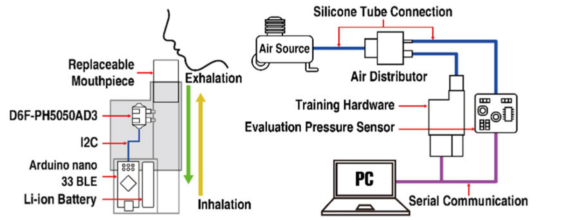

FIGURE 3. The air source is connected to the distributor through a silicon tube. The distributor transmits the airflow to the visual attention and pulmonary VR training system for children with ADHD and pressure sensors for evaluation through 4 mm and 9 mm silicon tubes, respectively. The measured values of the proposed system and the evaluation pressure sensor are recorded simultaneously in real time on a single computer.

IV. EXPERIMENT

A. PARTICIPANTS

To verify the effectiveness of the proposed training system, 12 participants (five males (42%) and seven females (58%)) in the experimental group and 12 participants (five males (42%) and seven females (58%)) in the control group were selected (Table 2). For testing the effectiveness of the VR training system, 24 children with ADHD were assigned to two groups: a group that performed pulmonary VR training and a control group that did not perform pulmonary VR training. Both groups had the psychomotor program [26] in common, which aims to treat children's ADHD. Initial pre-test measurements of visual ATA in the experimental and control groups did not show significant differences: omission error (t=-0.231, $p>0.05$), commission error (t=-0.049, $p>0.05$), and visual ATA (t=0.418, $p>0.05$). The initial pre-test measurements of pulmonary function did not show significant differences: MIP (Maximum Inspiratory Pressure, t=-0.030, $p>0.05$), MEP (Maximum Expiratory Pressure, t=0.037, $p>0.05$), FEV1 (Forced Expiratory Volume in 1 s, t=0.087, $p>0.05$), and FVC (Forced Vital Capacity, t=0.130, $p>0.05$). FEV1 and FVC present the volume of one expiratory breath. In one breath that uses maximum effort to breathe out all air (i.e., forced breath), FEV1 shows the volume of the initial 1 s of breath.

FVC shows the whole volume of the forced exhalation breath. MIP and MEP each represent the maximum power

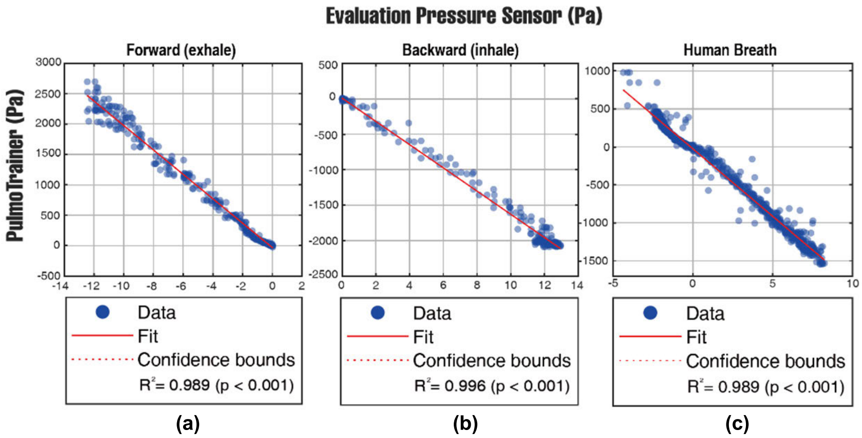

FIGURE 4. Three evaluation results showed that the user's breathing input was accurately evaluated. (a) shows the forward pressure, which means exhaling breath, and our device's data showed high linearity with commercial air pressure sensor data (R2=0.989). (b) shows the backward pressure, which means inhaling breath, and it showed high linearity with commercial air pressure sensor data (R2=0.996), and (c) shows the evaluation results when a person breathes in and out continuously and it also showed high linearity with commercial air pressure sensor (R2=0.989). For human breath, a male adult's breath was used.

of breath when inhaling and exhaling. The omission error in the ATA was the number of times a participant missed pressing the button when the target stimulus was presented. The commission error was the number of times a participant pressed a button when the target stimulus was not presented.

B. TASK

A minimum of eight sessions and three weeks of training were required to see improvements in breathing and visual attention training. To control the natural growth of respiratory function due to the growth of growing participants, all participants were trained for a total of eight sessions for at least three weeks but no more than four weeks from the first session. All participants were trained following a six-step integrated psychomotor program [26] for ADHD (Table 3).

Additionally, participants in the experimental group followed a Latin-square design for the order in which they played the three games of VR training to minimize order effects during the eight training sessions.

C. EXPERIMENT DESIGN

A between-subjects design was used in this study to test the effectiveness of attention improvement. To validate the improvement in respiratory function and attention, pre-and post-test comparisons within the experimental group and pre-post comparisons between the experimental and control groups were conducted.

D. PROCEDURE

Prior to experimenting with children, who were vulnerable research participants, evidence about research methods and the protection of human subjects was submitted to the Institutional Review Board (IRB) to receive approval. Subsequently, a pulmonary training device connected to a smartphone was installed in a sports therapy center for children. The training sessions were conducted by exercise therapists who work with children with ADHD. Before starting the session, the experimenter obtained a signed consent form from the participants and their parents (or legal guardians) if they agreed to participate in the study. After undergoing visual ATA and pulmonary function measurements, the experimenter introduces participants to the games and how to play them (how to interact with the game through breathing and proper breathing techniques). In each training session, participants were instructed to play all three games, and the order in which they played the games was designed to minimize the learning effect of the games through the Latin-square design. Each training session lasted about 15 min. After completing eight training sessions within four weeks, at least twice a week, participants completed nine questions regarding the experience with the game (SUS, Slater-Usoh-Steed presence questionnaire [46]), along with the visual ATA and PFT. After the measurements, the experimenter interviewed each participant about their experiences and preferences with each of the training games, experiences with interacting with breathing, and thoughts during training to collect qualitative data.

E. MEASURES

The experimental and control groups took the ATA [27], [28] before and after the experiment. The ATA is a computerized attention test widely used in South Korea and Japan. ATA is divided into two types: one with visual stimuli and one with auditory stimuli. In visual ATA, participants are asked to memorize a target visual stimulus and then perform the task of pressing a button only when the target stimulus is presented among a variety of periodically presented visual stimuli.

TABLE 2. Participant demographics and pre-test visual ATA and pulmonary function values.

Group	Category		Characteristic
Experiment (n=12)	Gender	Male	5(42%)
		Female	7(58%)
	Age	8	2(17%)
		9	1(8%)
		10	2(17%)
		11	2(17%)
		12	3(25%)
		13	2(17%)
	Visual ATA	Omission error(M/SD)	67.33(14.196)
		Commission error(M/SD)	54.92(11.261)
		Overall(M/SD)	130.33(5.598)
	Pulmonary function	MIP(M/SD)	36.08(14.029)
		MEP(M/SD)	55.33(28.452)
		FEV1(M/SD)	1.70(0.475)
		FVC(M/SD)	1.84(0.508)
Control (n=12)	Gender	Male	5(42%)
		Female	7(58%)
	Age	8	2(17%)
		9	1(8%)
		10	2(17%)
		11	2(17%)
		12	3(25%)
		13	2(17%)
	Visual ATA	Omission error(M/SD)	68.33(4.849)
		Commission error(M/SD)	55.08(3.630)
		Overall(M/SD)	129.42(5.143)
	Respiratory function	MIP(M/SD)	36.25(13.123)
		MEP(M/SD)	54.92(26.480)
		FEV1(M/SD)	1.69(0.462)
		FVC(M/SD)	1.82(0.497)

In ATA, a total score of 100 for each sense was the normal mean, a score of up to 115, +1 SD, was considered normal; a score of up to 123, +1.5 SD, was suspected of ADHD; and a score above that was diagnosed as ADHD. With a normal score of 60 for omission and commission errors, a score up to 63, +1.5 SD, was considered normal, and a score up to 65, +1.5 SD, was suspected of ADHD. After completing the eight training sessions, participants in the experimental group were asked to answer the SUS questionnaires [46], which were used to measure the presence and the immersiveness of the system. In addition, to determine whether respiratory function improved, the intensity and volume of breathing were measured in the experimental group before the first training session and after the eighth session using validated devices used in the medical field, the CafeFusion MicroLab ML3500 [47] (Fig. 5a) and the CareFusion MicroRPM [48] (Fig. 5b).

F. ANALYSIS

For the experimental result data, we first performed the Shapiro-Wilk test to assess the normality of the data. All three items of attention (visual ATA, omission error, and commission error) and all four items of pulmonary function

TABLE 3. Six steps of psychomotor program for ADHD.

Steps	Activity
Step 1	Sense of Balance and Motor Activity
Step 2	Halting and Motion Control
Step 3	Improving Concentration with Closed Eyes
Step 4	Improving Visuotactile Concentration
Step 5	Overcoming Impulsivity
Step 6	Self-Control through Physical Activities

(MIP, MEP, FEV1, and FVC) met normality. So, the Unpaired t-test was used for the comparison between groups, and the Paired t-test was used for the pre-post comparison within the group to analyze whether there was a significant difference.

V. RESULTS AND DISCUSSIONS

A. RESULTS

To test the two hypotheses of this study, we conducted user experiments using our VR training system with children having ADHD in a four-week. The visual attention of the participants improved significantly in omission error, commission error, and overall score of ATA. As for the pulmonary function, among maximum inhalation pressure (MIP), maximum exhalation pressure (MEP), forced expiratory volume in one second (FEV1), and forced vital capacity (FVC), there was significant improvement in MIP, MEP, and FVC.

The Shapiro–Wilk tests were performed to check the normality of the attention improvement, and all three items (pre- and post-test visual ATA, omission error, and commission error) met normality ($p>0.05$). Paired t-tests were performed for pre- and post-test comparisons in the experimental group, showing significant differences in omission error (t=5.692, $p<0.001$), commission error (t=3.764, $p<0.01$), and visual ATA (t=9.570, $p<0.001$) (Table 4). In all three items, there was a significant decrease, which indicates visual attention was significantly improved.

Unpaired t-tests were performed to compare the pre- to post-treatment changes between the experimental and control groups; they showed significant differences in omission error (t=4.799, $p<0.001$), commission error (t=3.566, $p<0.01$), and visual ATA (t=5.106, $p<0.001$) (Table 5). In all three items, there was a significant decrease, which indicates that visual attention improvement was significantly better in the experimental group than in the control group. In the control group, the commission error score increased, which indicates that the control group had more commission errors in the ATA test after treatment.

As a result of performing the Shapiro–Wilk tests for respiratory function improvements, normality was met ($p>0.05$) for MIP, MEP, FEV1, and FVC. Paired t-tests were performed for pre- and post-test comparisons in the experimental group, showing significant differences in MIP (t=-4.235, $p<0.01$), MEP (t=-2.669, $p<0.05$), FEV1 (t=-2.479, $p<0.05$), and FVC (t=-3.19, $p<0.05$) (Table 6).

Unpaired t-tests were performed to compare the pre- to post-treatment changes between the experimental and con-

FIGURE 5. (a) MicroDirect ML3500 spirometer device is used for measuring the volume/time for inhaling and exhaling each breath. (b) MicroDirect MicroRPM device is used for measuring the inhaled and exhaled breath pressures.

trol groups; they showed significant differences in MIP (t=-3.880, $p<0.01$), MEP (t=-2.243, $p<0.05$), and FVC (t=-2.185, $p<0.05$) (Table 7).

Training with the proposed system significantly improved the pulmonary function in MIP, MEP, and FVC.

On the SUS questionnaire, scored on a 5-point Likert scale, the participants gave an average score of 3.917 to the "Did you focus on the game?" item, 3.417 to the "game presence" item, and an average score of 4 or higher for the "difficulty," "fun," "ease of operation," and "Do you want to play it again?" items.

B. DISCUSSIONS

The developed system showed significant effects as a tool to improve visual attention and pulmonary function in children with ADHD. The findings from the experiments supported hypothesis 1 and partially supported hypothesis 2, showing improvement in only MIP, MEP, and FVC.

1) VISUAL ATTENTION

The task and VR environment design of our game is supposed to be the main factor for improving visual attention. Unlike psychomotor programs in the real world, there is no element in the environment of our VR training system that can distract participants. Due to this variable control, the effect of improving the visual ATA score seems to be different. All three games require users to make eye contact with the object that they want to interact with. The children with ADHD seemed to have embodied the method of visual attention by focusing their visual attention on the objects that they wanted to influence. This is supported by the increase in the number of children that completed the Food game, which has the smallest object and requires the highest visual attention ability. Five of the 12 subjects completed up to the second sequence of three games in the first of eight training sessions, but by the fourth session, all participants completed all three games. The average time taken to complete the food game decreased from 397.906 s in the first session to 282.112 s in the eighth session, indicating that the visual attention training was effective.

TABLE 4. Statistical significance of pre- and post-test for visual attention in the experimental group.

		M(SD)	t(p)
Omission error	Before	67.33(14.196)	5.692***
	After	52.58(8.847)	
Commission error	Before	54.92(11.261)	3.764**
	After	50.17(10.205)	
Overall	Before	130.33(5.598)	9.570***
	After	121.25(5.479)	

** $p<0.01$, *** $p<0.001$

2) PULMONARY FUNCTION

RMT is a traditional and widely used training method. RMT uses an apparatus that allows resistance to breathing for training volume and pressure. However, in previous studies, the effects of changes in breathing volume and pressure varied according to the training method, period, and subject [23], [24]. The results of this study differed from those of a five-week RMT program in soccer players, which showed improvement in MIP and no change in FEV1 or FVC [23], as well as a study in swimmers, which showed improvement in FVC [24]. In this study, only the changes in FVC, MIP, and MEP were significantly improved compared to the control group, with no change in FEV1. There could be two possible explanations for this trend.

First, there may not have been enough resistance induced by the developed training system when the participants were breathing.

The respiratory muscles grow by recovering from muscle fatigue through progressive overload [49]. The intensity, not quantity, of breathing exercises is crucial for the growth of breathing pressure [23]. The intensity of the respiratory training with the proposed system was determined by the tapered hardware structure. The muscles responsible for the intensity of breathing may not have grown as the physical stress on the respiratory tract was not strong enough to cause an increase in FEV1. In contrast, breathing exercises such as PFT (i.e., breath required during a PFT, requiring one to inhale and exhale strongly, quickly, and for as long and as many breaths as possible) may have been consistently practiced, thereby improving other metrics.

Second, the children may have learned with regards to using their breathing ability, during training sessions. The style of breathing required in the training sessions of the experiment involved inhaling and exhaling for as long and as many breaths as possible. Breathing for PFT should be performed as strongly and continuously as possible (at least 6 s for adults and at least 3 s for children [50]) such that no air remains in the lungs. Even adults with normal pulmonary function find it difficult to exhale long enough to leave no air in the lungs. For this reason, children with ADHD have difficulty with PFT breathing. However, after four weeks of training, they may have become accustomed to maximizing their PFT breath, leading to better pulmonary

TABLE 5. **Statistical significance of pre- to post-test changes in visual attention between the experimental and control groups.**

		M(SD)	t(*p*)
Omission error decrease	Experiment	14.75(8.976)	4.799***
	Control	1.67(2.934)	
Commission error decrease	Experiment	4.75(4.372)	3.566**
	Control	-1.08(3.605)	
Overall ATA decrease	Experiment	9.08(3.288)	5.106***
	Control	0.83(4.529)	

** $p<0.01$, *** $p<0.001$

TABLE 6. **Statistical significance of pre- and post-tests for pulmonary function in the experimental group.**

		M(SD)	t(*p*)
MIP	Before	36.08(4.050)	-4.235**
	After	58.50(6.976)	
MEP	Before	55.33(8.213)	-2.669*
	After	75.42(8.891)	
FEV1	Before	1.70(0.137)	-2.479*
	After	1.91(0.160)	
FVC	Before	1.84(0.147)	-3.19*
	After	2.16(0.201)	

* $p<0.05$, ** $p<0.01$

TABLE 7. **Statistical significance of pre- to post-test changes in pulmonary function between the experimental and control groups.**

		M(SD)	t(*p*)
MIP change	Experiment	22.42(18.338)	3.880**
	Control	1.83(1.193)	
MEP change	Experiment	20.08(26.064)	2.243*
	Control	3.17(1.801)	
FEV1 change	Experiment	0.21(0.289)	0.795
	Control	0.14(0.086)	
FVC change	Experiment	0.31(0.341)	2.185*
	Control	0.09(0.084)	

* $p<0.05$, ** $p<0.01$

function measurements than before training. However, even after considering this, a change of 0.21 L in FEV1 was still a significant enough improvement in lung function when compared to the average FEV1 growth and growth trend for the age group participating in this study. Furthermore, for this reason, the difference in MIP and MEP change was relatively greater in the experimental group than in the control group.

For an average age of 10.4 years among the participants, the average FEV1 growth in one year was 0.238 L [51]. Statistics from previous studies have shown that the average pulmonary function growth graph for this age group is arithmetic rather than logistic [52]. Therefore, the annualized growth figure divided by 12 (FEV1 0.020L) was not too far off from the average monthly growth. In other words, the increase in participants' FEV1 in this study indicated a significant training effect.

As shown in Fig. 6, most of the participants became familiar with PFT breathing in terms of breathing patterns. When PFT breathing is performed faithfully, the breathing graph falls into the gray area in Fig. 6a. Fig. 6a is the graph of PFT of Participant 1 (P1) before the training session, and Fig. 6c is the graph of the first breath of P1's first training session. The shape of the graphs in Figs. 6a and 6c fall short of the shape of the gray area in Fig. 6a. Fig. 6b is a graph of the PFT at the end of a training session, and Fig. 6d is a graph of the last breath of the last training session. The shape of the graphs has become much closer to the shape of the gray area compared to Figs. 6a and 6c. Previous studies have shown that having users focus on their breathing while playing VR games with breathing as input increases their awareness of their breathing patterns and body movements [53], [54]. The participants' improved breathing patterns may have also been a result of increased self-awareness. This process of getting used to PFT breathing can also happen during the breathing measurement process outside of the VR training system. Therefore, the participants in the control group may also have become accustomed to PFT breathing and learned to increase their FEV1, resulting in no significant difference in the between-subjects data for FEV1. This is significant, as familiarization with PFT breathing could facilitate the diagnosis of pulmonary problems in children with ADHD. The participants' ability to control their inhalation and exhalation increased with the experimental treatment, which is supported by existing studies that have demonstrated an increase in breathing capacity as well as breathing control.

3) EFFECT OF TRAINING

In this study, VR was selected as the training medium, assuming the motivation and active participation of ADHD patients. The effectiveness of immersive learning in VR has been well-researched and established [32]. In the conducted experiments, nine out of 12 participants in the experimental group said in interviews that they enjoyed it and wanted to do more. Of the 12 subjects in the experimental group, eight preferred the Rocket game, and four preferred the Food game.

Among the theories explaining the user's immersion, there is the 'Flow' theory [55], [56]. When the user enters the '*Flow*' state while using the specific medium, the sense of time is altered, and the sense of self is lost. This is similar to the state of the user immersed in the game in Brown and Cairns' theory of game immersion [30]. The game immersion theory divides the stage in which the user is immersed in a certain medium into three stages: *Engagement*, *Engrossment*, and *Total immersion*. The engagement stage is the lowest stage of immersion. Game users must invest time, effort, and attention, and it is difficult to get the user to enter the engagement stage for games that do not suit the user's preferences. The engrossment stage is a stage in which the user becomes more immersed in the game. When there is a structure in which the user can focus on the game in the engagement stage, the user can enter the engrossment stage. At this stage,

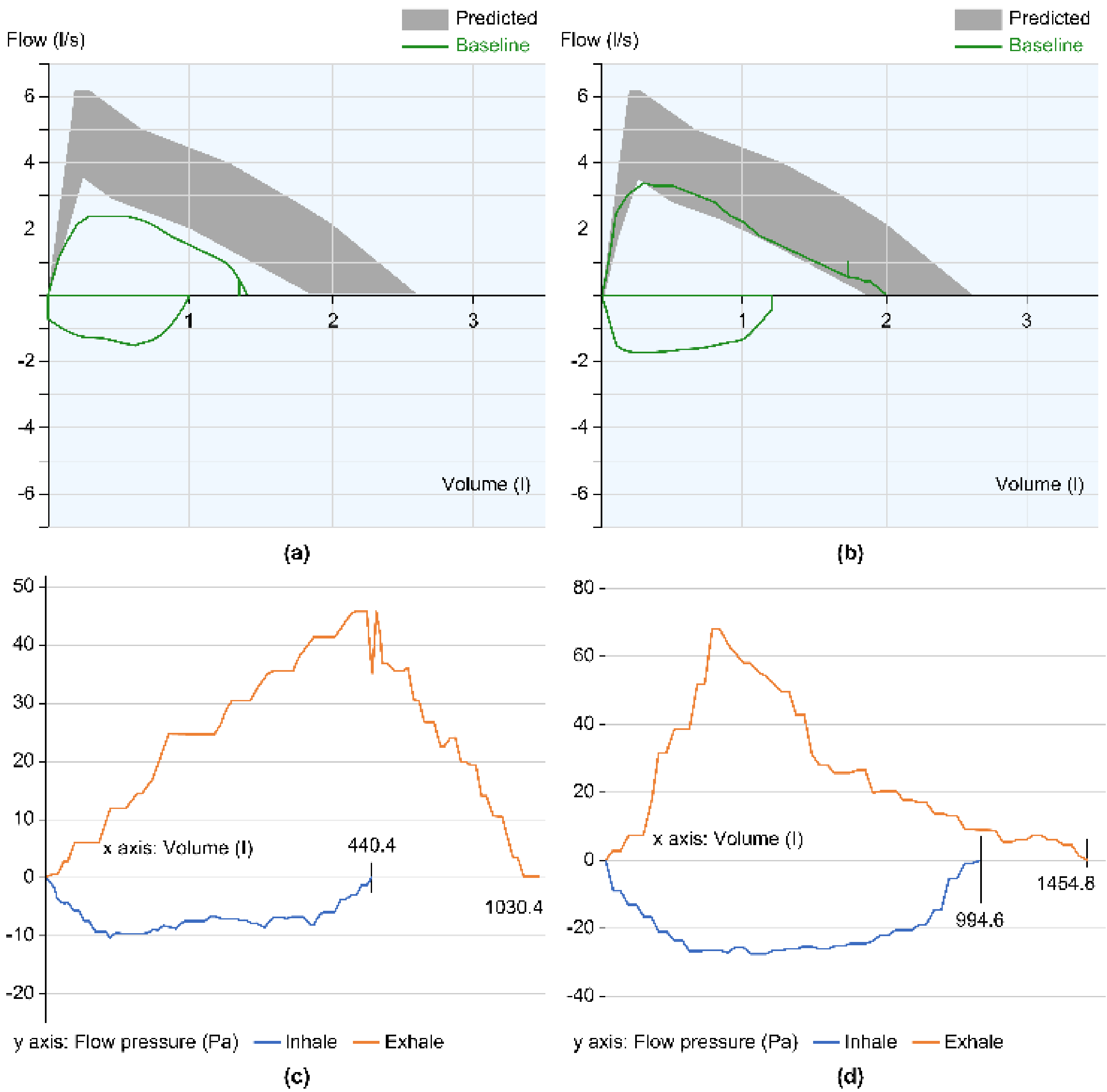

FIGURE 6. **(a) Participant 1's PFT data graph before treatment. (b) Participant 1's PFT data graph after treatment. (c) One of Participant 1's breathing graphs in PulmoTrainer treatment 1. (d) One of Participant 1's breathing graphs in PulmoTrainer treatment 8.**

the user's emotions are directly affected by the game. To reach the last stage, Total immersion, the game needs to induce empathy for the user and create an appropriate atmosphere. At this stage, the user is separated from everything other than the game, including reality. In our VR training game, participants showed that they felt high presence and high immersiveness by giving a high score of 4 or more to the SUS questionnaires asked on 5-Likert scales. The three steps to reach the 'Flow' state were clearly identified in Participant 6 (P6)'s interview. P6 in the experimental group tried to take off the HMD due to a fear of the heights of the rocket. Nevertheless, P6 completed the exercise with praise and reassurance from the exercise therapist. Moreover, P6 said in an interview "At first I didn't want to do it because I thought I might get sick, but by the third session, I felt it was safer and more fun than I first thought." P6 did not want to play the game in the first phase, engagement, because it would require effort to adapt the game. Since there were no issues with the game's structure that would break the *Flow*, P6 was able to invest the time and effort to reach the second stage, Engrossment. This made P6 fun and allowed P6 to reach the deepest level of game immersion, Total immersion.

Breathing is a physiological activity that must be maintained even when not used in a game, and excessive use of it can lead to the perception of real-world discomfort, breaking the flow. However, based on the observations of the experimenter, the ADHD patient's caregiver, and the psychotherapy specialist at the institution where the experiment was conducted, none of the participants in this study made comments suggesting that they were "out of breath" after each training session. Rather, several participants made comments such as, "When the training session is over, I'm going to go play with my friends" (P2) or "Now that the training is over, can I go play soccer? (P7). This meant that the load on the respiratory system was not overwhelming. Furthermore, immediately after each of the eight training sessions, the participants asked, "Are we done already?" an average of 4.5 times. This was a transcript of the interview, which suggested that the participants were in a flow state during the training session. Flow refers to a state in which the user is fully immersed in the action of the game and becomes more attentive and engaged, enjoying the activities they do in the game [55], [57]. In addition, items implying quick passing of time indicated that the participants exhibited an "altered sense of time" [56], [58], which was one of the hallmarks of the flow state. This suggested that the physiological load of using breathing input may have created a trade-off between flow and pulmonary function training.

All 12 subjects preferred either the Rocket game or the Food game. According to the participants' interviews, they preferred the Rocket because "it was fun to see the rocket crumble and fly away as if it were gathering strength" (P5), and "the special effects that were launched under the flying rocket were fun" (P7). Reasons for preferring the Food game included, "It was fun to see the food spin around as if it were being sucked into my mouth" (P1) and "I liked the swirling effect of the wind as the food was sucked in" (P3). Eight of the participants who preferred the Rocket or Food game mentioned the visual effects in their interviews. A study by Sra et al. suggested that when developing VR games with breathing input, the intuitiveness of interacting with breathing could be improved by showing activities that matched breathing [21]. Considering the similarity with the proposed design guides in the study by Sra et al. [21], the interaction was properly implemented in training for improved visual attention and pulmonary function for the Rocket and Food games of the proposed training system.

VI. CONCLUSION

In this paper, we present a novel visual attention and breathing training system using VR. The concept, design, and development of the VR training system are discussed. This new VR training system directly utilizes the subject's breathing-measured air pressure sensor to provide immediate visual feedback. To provide enjoyable training, we designed training software that can make users immersed in the training process and let them invest their attention. Through the user experiment, we found that ADHD treatment with VR gamification has a significant effect. There were around 20cmH2O (a unit that measures the pressure of respiration through the height at which the water column is pushed out during exhalation or inhalation) improvements in MIP and MEP, and 0.31 improvement in FVC in the experiment group's pulmonary functions. Also, there were improvements in the ATA visual attention test regarding the decrease in omission error count (14.75), commission error count (4.75), and overall visual ADHD score (9.08). Through PFT and visual ATA results, we confirmed the possibility of expanding the intervention using VR serious games for pulmonary and visual attention training. In the future, we plan to improve our new VR training system such that it can treat other symptoms of ADHD. This improved system will be compared with other interventions.

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