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Eye-Contact Game Using Mixed Reality for the Treatment of Children With Attention Deficit Hyperactivity Disorder

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ABSTRACT Many children with attention deficit hyperactivity disorder (ADHD) perform poorly in their academic studies. They also have difficulties in their social lives due to a lack of interpersonal skills and this often continues into adult life. Appropriate early therapies and medications can be very beneficial. In this paper, we introduce and demonstrate the benefits of a new type of treatment, namely, an eye-contact game which successfully exploits mixed reality technology. None of the patients in our experiment were older than ten years of age. They were able to pay attention and sustain interest in the treatment sessions over a span of six weeks. After participating in the treatment sessions with our game, the omission/commission errors which were evaluated in an attention test taken by the experimental group decreased significantly and appeared within the normal range. In addition to the improvement in error rates, the mean response time to an interactive metronome test significantly decreased. Importantly, our game allows patients to conduct this treatment by themselves at home without professional assistance. To the best of our knowledge, this study is one of the first studies to use a mixed reality head-mounted display to treat children with attention deficit hyperactivity disorder and to prove its potential as a treatment for clinically diagnosed children.

INDEX TERMS Virtual reality, augmented reality, medical treatment, medical information systems, face detection.

I. INTRODUCTION

The Diagnostic and Statistical Manual of mental disorders (DSM) [1] characterizes people with attention deficit hyperactivity disorder (ADHD) as those with elevated levels of hyperactive, impulsive, and inattentive behavior. People with ADHD can be primarily categorized into three subtypes: predominantly inattentive, predominantly hyperactive/impulsive, or a combination of both. With regard to aspects of perception and learning, ADHD patients have difficulty in maintaining attention, concentrating on specific procedures related to learning or task performance, and transitioning from one task to another due to their limited ability to sustain attention [2]. Furthermore, not being easily motivated, they easily become bored, they have problems tempering their reactions and they have difficulty with cognitive functions, such as working memory, executive function, and attentiveness [3]. These characteristics are the main causes of poor academic performance, low self-esteem, and interpersonal problems.

Three to eleven percent of children are estimated to exhibit ADHD in elementary schools in America [4]–[6]. In addition, 54,986 cases of children with ADHD were reported in South Korea in 2013. ADHD is a serious problem in South Korea, with the number of patients increasing annually by 4.24% on average from 2009 to 2013. Furthermore, DSM-5 [7] specifies that ADHD patients can experience symptoms even after they have developed from children to

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adolescents. Although hyperactivity and impulsivity disappear in many cases, the potential for experiencing difficulties in academic achievements and social lives owing to the lack of attention remains high, and the success rate for ADHD treatment becomes lower with age. Consequently, early and appropriate treatments for ADHD are important.

To treat ADHD, many medications and therapies are currently in use. Medications such as methylphenidate, lisdexamfetamine, and dexamphetamine can be used [8], but side effects may occur. In addition, therapies such as psychoeducation, behavioral therapy, parent training and education programs and cognitive behavioral therapy can be used. However, these therapies require not only well-trained specialists but also dedicated space and time; thus, many ADHD children lose interest in the programs and they give up treatment. As a result, there is an increasing need for instructional programs that can be applied to ADHD children without them losing interest or spontaneity; the ready availability of the engaging therapeutic device would bring benefits within the reach of all children with ADHD [9].

With recent advances in information technology, several researchers have reported that technologies such as virtual reality, mobile devices, and digital games can be used to treat ADHD patients. For example, Akili Interactive Labs, Inc. developed a mobile game called "AKL-T01" to treat ADHD patients, and its effects were proven in 348 children [10]. In addition, a simple virtual reality program was used for the treatment of ten children with ADHD, and their omission/commission errors decreased significantly compared with a control group [11]. Beyond these technology-based treatments [12], we researched and evaluated new opportunities to leverage mixed reality to enhance the lives and functionality of children with ADHD.

One of the intervention methods for social interaction deficiency in the ADHD group is social skills training (SST), which is a behavioral intervention based on learning theory [13]. SST teaches ADHD groups the social skills that individuals need (e.g., greetings and conversation) through behavioral techniques such as reinforcement with rewards. Although SST has been repeatedly proven effective as an intervention treatment for social interaction deficiency of ADHD [14], there is a practical limitation of this treatment in that it takes time, manpower, and cost, as it is necessary to teach each skill directly under the guidance of an expert [15].

Recently, based on the fact that faces contain information essential for social interaction, attempts have been made to intervene in deficits of social interaction in the ADHD group in terms of facial recognition [16], [17]. Furthermore, several theories have proven that there is a correlation between abnormal face recognition and difficulties in social interaction for children with ADHD [18]–[20]. The first group of theories explains that ADHD people have a weak central coherence (WCC) phenomenon, which is a cognitive bias which prevents them from effectively processing faces [18]. According to this theory, although normal people integrate and process the detailed features that make up the face in one overall template, people with ADHD exhibit a perceptual bias to only some features or parts of the face, thereby preventing efficient face recognition.

The second group of theories argues that the eye-evasion hypothesis, which ADHD people have in common, also affects ADHD people's facial treatment. According to this theory, when looking at people, normal people focus on the eyes and the surroundings of the eyes, which provide the most essential information for face recognition. However, people with ADHD tend to look around the periphery, such as mouth or nose, and thus, this atypical attention pattern causes difficulties in face recognition [19], [20].

Based on these theories, in this paper we introduce a Mixed Reality Head Mounted Display (MR HMD) based eye-contact training game as another intervention method that can enhance the attention and sociality of people with ADHD. We designed a serious game using MR to adequately treat ADHD children with face perception and social enhancement. Comparative pre- and post-test results were obtained for twenty ADHD children exposed to the game during 15 sessions over 6 weeks. Furthermore, we compared these results with those of another group of twenty ADHD children who did not have access to this treatment.

The contributions of this work can be summarized as follows. First, we investigated and developed a novel MR eye-contact game for the treatment of children with ADHD. Next, we verified that the eye-contact game that we developed improved the children's visual attention. Subsequently, we proved the effectiveness of the game with clinically diagnosed ADHD children based on widely used tests such as the advanced test of attention (ATA), the interactive metronome (IM), and a survey. To the best of our knowledge, this work is one of the first studies using an MR HMD as a tool to treat children with ADHD.

This paper is organized as follows. Section II discusses related works. Section III describes the design and implementation of the game. Section IV presents the results of the game experiment when used on ADHD children. Section V is a summary conclusion.

II. RELATED WORKS

This section introduces some background and related works for a better understanding of our study.

A. GAMES AS MEDICAL TREATMENTS

Technological breakthroughs and the interesting characteristics of certain games have recently resulted in the development of games for medical purposes, where users can continue treatment without losing interest [7], [11]. For example, an electronic game called "AKL-T01" has been shown to be effective in treating ADHD patients [10]. The developers investigated the effectiveness of the game on children with ADHD and reported that the attention and impulse control of those children improved relative to those using a placebo [21].

In addition to AKL-T01 for ADHD patients, Amblyotech, Inc. has introduced a mobile game called "Dig Rush" [22] to treat children with amblyopia; James Blaha has offered a game called "Diplopia" using virtual reality [23], which can be used for people with lazy eye (amblyopia) and crossed eye (strabismus). Furthermore, Vivid Vision, Inc. has created a VR-based game for children with convergence insufficiency [24].

B. VIRTUAL/AUGMENTED REALITY (VR/AR) FOR ATTENTION DEFICIT HYPERACTIVITY DISORDER (ADHD) PATIENTS

There are several reasons why VR or AR can be effective for ADHD patients. Most importantly, it is possible to raise their attention and motivate them to continue with the treatments through immersion and presence by providing a spatial and temporal experience similar to reality [25], [26]. This approach also encourages interaction with objects in virtual reality by manipulation or commands through engaging devices that promote spontaneous learning and cognitive function through natural behavioral practice [27], [28]. Such environments can also be and feel safer for learning; nonthreatening learning environments are more effective than less sensitive competitive real-world environments [27], [29]. A variety of environmental conditions can be configured to repetitively perform a specific task and to teach or acquire an understanding of the concepts [30]. Due to such advantages from VR/AR-based interventions, researchers have found that children with emotional and behavioral disabilities have benefited in areas of social behavior [31], including eye contact, cognitive requirements such as memory functionality and sensory processing, and various kinds of attention such as focused attention, sustained attention, selective attention, alternating attention and divided attention [32], [33].

C. ADVANCED TEST OF ATTENTION (ATA) AND INTERACTIVE METRONOME (IM)

ATA [34] is widely used in Korea for the diagnosis of ADHD [35]; its usefulness has been verified in Japan [36]. ATA measures visual and auditory attention using a computer and can be executed by children and adolescents aged 5 to 15 years. ATA has been used to study the difference between children with ADHD and autism spectrum disorder in [37], and its characteristics according to intelligence levels have been investigated [38].

On the other hand, IM is a measurement tool for evaluating timing and a training tool for improving attention [39]–[44]. It comprises a computer, software, and devices such as a hand trigger, foot trigger, and headset. The triggers, which are tapped by the user, send the relative timing information to the computer system, which is equipped with the IM training software during the task. The system analyzes the information and measures the accuracy of the trigger tapping in milliseconds. When the mean response difference time approaches 0, the response becomes more accurate. The attention, motor control, language, and aggression control of 19 children with ADHD treated by IM training improved, as noted in the literature [40]. In another study, IM training for 12 sessions over 4 weeks improved the foot taps timing of the participants [42]. Furthermore, the complex visual selection reaction time and visuomotor control of children with ADHD and of children with developmental coordination disorder were significantly improved; however, their sustained attention or motor inhibition were not improved significantly [44]. In [41], an IM was used as an evaluation and training tool, and the improved timing, attention, working memory, and processing speed of ADHD children were demonstrated.

In this study, we measured the ATA and IM scores before and after treatments to observe the impact of our game.

III. GAME SEQUENCES AND IMPLEMENTATIONS

This section describes the game sequences and implementations of our treatment. Our treatment consists of 3 levels, 5 sessions, 3 modes, 2 sets and 6 games. In other words, the participant plays the game 36 times (3 modes × 2 sets × 6 games) in a single session (visit) and plays the game 540 times in total (3 levels × 5 sessions × 3 modes × 2 sets × 6 games) during the entire treatment. The levels represent the overall difficulty of each session, which increases every 5 sessions. A single session is completed when a participant has visited and included 3 different modes. Each mode has its matching range and period, which will be illustrated later in this section. A set including 6 eye-contact games was designed and used in the trials. We added the concepts of level and mode after the pilot studies because the ADHD participants became bored and lost their attention with the sameness and with the same difficulty levels. After the pilot studies and considering the attention period of the ADHD participants, we added the concepts of sessions, sets and games so that participants could finish each session within 30 minutes.

The sequences of a single game are as follows. Our game shows an introductory screen in the HoloLens as it starts. The game parameters are then set, and we subsequently proceed with the game as the start button is pressed. The game then starts drawing the outline of a face, and the participant tries to match the outline to a partner's real face through a camera. This eye-matching activity is repeated six times, and two sets of matching processes are performed for each mode.

One partner is required to assist the participant throughout our game. The participant is a child with ADHD, and the partner could be a parent or a teacher. Overall, the partner runs our game through the menus in the HoloLens, sets the level in the introductory scene, and starts the game, as illustrated in Figure 1.

Figure 1 shows the sequence of our game. When the game starts, it displays an introductory screen, which allows the mode of the game to be selected, provides a leaderboard, and offers the option to start the game on the HoloLens. The game partner can select the degree of difficulty, following which the screen changes to the option of mode selection where the partner can select one level from "easy," "general," and "difficult." If the participant is familiar with these procedures, he or she can set up the game and play without the aid of a partner/assistant. However, in our trials, a partner set

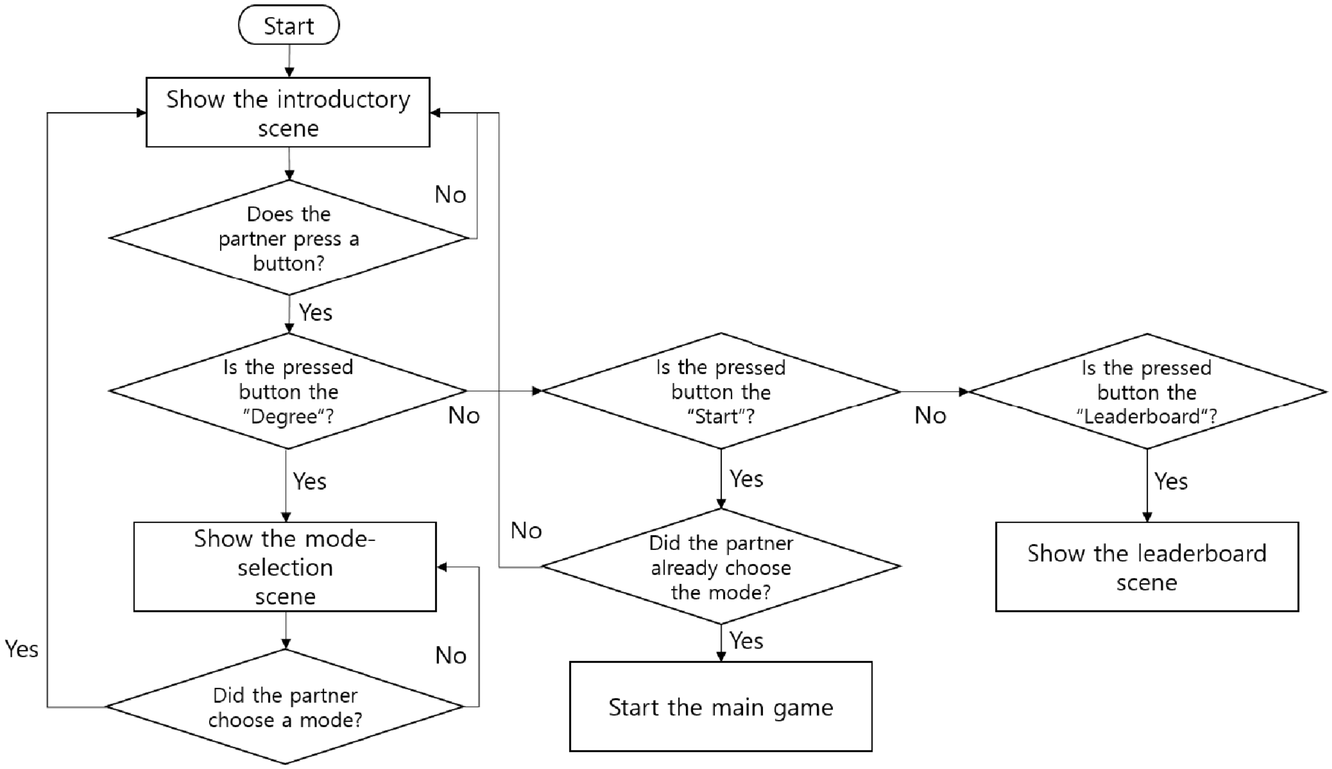

FIGURE 1. Game setting sequences by the partner.

the game up for this study because the participants were not familiar with the environment or the procedures.

The modes shown are related to various parameters, namely, the matching range accuracy between the outline of a face which is displayed by the camera embedded in the HoloLens and the partner's real face through the lens, and the matching period (i.e., the duration the matching is maintained). We used the matching range accuracy to measure whether the children with ADHD looked at the partner's face correctly, and we used the matching period to measure whether the children could sustain their visual focus. These criteria become harder to meet as the experiment proceeds. Table 1 shows the values of the criteria for matching range accuracy and matching period for each level and mode.

As shown in Table 1, the matching range accuracy is 0.7 mm, and the period changes from 1 to 2 s in each mode for the first five sessions. This implies that the participant should match the face outline with the real face passing within a 0.7 mm distance gap over 1 to 2 s. In the next five sessions, the gap for accuracy decreased to 0.5 mm, and the duration for watching (focused attention) increased to 1.5 ~ 2.5 s. In the final five sessions, the distance gap for accuracy decreased to 0.3 mm, and the duration for watching increased to 2 ~ 3 s based on each mode of easy, general, and difficult.

To determine the parameters shown in Table 1, we performed pilot studies with children clinically diagnosed with ADHD and designed the parameters such that the children could finish playing the game within 30 minutes because a longer playing time might have caused them to lose focus.

TABLE 1. Level settings of the game.

Level	Mode	Matching range accuracy (mm)	Matching period (second)
5 sessions	Easy	0.7	1
	General	0.7	1.5
	Difficult	0.7	2
5 sessions	Easy	0.5	1.5
	General	0.5	2
	Difficult	0.5	2.5
5 sessions	Easy	0.3	2
	General	0.3	2.5
	Difficult	0.3	3

In addition, different background music (BGM) was played at each level to refresh and sustain the children's interest.

After choosing the mode, the partner presses the "Start" button. Then, the main game runs the overall sequence shown in Figure 2. The partner then helps the participant fit the HoloLens on his or her head.

When the game starts, a voice and a message instruct the children to "find a face". After completing that task, the message and the voice instruct them to "look at the eyes." The difference between the "find a face" and "look at the eyes" messages is that the first message is shown when no face is detected by the HoloLens' camera, while the second message is shown when the children's gaze is not focused on partner's eyes through the camera. Once the gazing task is performed, the message changes to "keep watching" with a red progress bar.

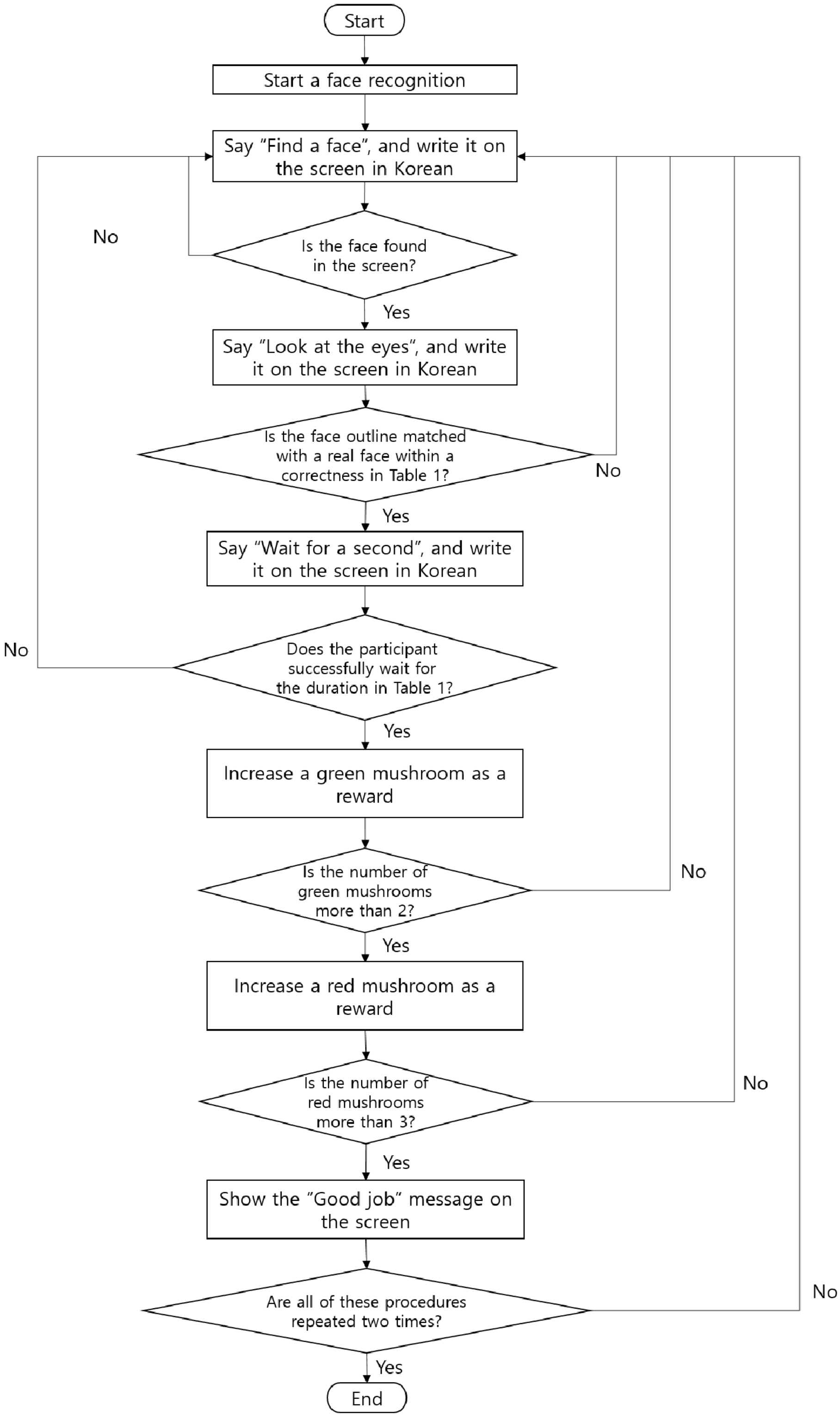

FIGURE 2. Game sequence by the participant.

If the children keep watching the partner's face successfully for the parameterized matching period, a green mushroom will appear as a reward. We decided to add the mushroom as a reward after conducting the pilot studies because the children wanted to see a reward (affirmation) when they completed a task. The number of green mushrooms increases, and a red mushroom appears when two green mushrooms are filled.

A mushroom appears when the children look at the partner's face. Children repeated the task until three red mushrooms are obtained, indicating that the children have looked at the partner six times in total (3 red mushrooms of 2 green mushrooms each). If all three red mushrooms are obtained, the children are rewarded with a final "good job!" message stamp.

This stamp marks the completion of one set; the second set starts immediately after that. After two sets have been completed, the next game starts in the "general" mode, as labeled in Table 1. Then, two additional sets requiring higher accuracy and duration are played for children to sustain their focus for longer periods of time. The mode tagged as "difficult" in Table 1 follows the successful completion of the "general" mode. We decided to play the game with three modes of two sets each after performing pilot studies with children with ADHD. We adjusted the game to continue for approximately 30 minutes after considering the attention sustainability of the children. To summarize, when a child visits for therapy, he/she plays a single session that consists of 36 eye-contact games (3 modes ("easy", "general" and "difficult") $\times$ 2 sets $\times$ 6 games). During the tests for the current study, we did not change partners because the change could have caused some confusion to the ADHD participant. In the leaderboard screen, the children can see the rankings of the top players. We added the leaderboard screen to motivate the children to repeat the game and aim for a higher ranking.

To develop the game, we used C#, which is included in Visual Studio 2017, Unity, and OpenCV [45]. We used OpenCV to perform face recognition because it has a high performance and a high recognition rate in the HoloLens platform. We used Unity because it enables us to conveniently create user interfaces by drag-and-drop.

The overall sequences of our game are shown in Figures 1 and 2. The implementation of our game can be summarized into the following steps. First, the camera is initialized and our game starts drawing the face outline in the display. Next, we start capturing and processing the video frames from the camera. The video is streamed into our game, and the extracted video frame is transformed into a texture. Finally, the OpenCV component analyzes each texture in the video stream and attempts to find a face in the texture. When OpenCV detects a face, our game measures the matching range accuracy between the face outline and the real face in the texture and creates both a corresponding thread and a progress bar above the face outline if the matching range accuracy is within the criteria. The thread continues to track a face and checks whether the face outline is matched with a real face through the HoloLens. If the ADHD children maintain their visual focus on the partner's eyes for a given matching period, the thread is completed, and a green mushroom appears as a reward. If the ADHD children cannot maintain focus during the matching period, our game restarts the process of finding a face in the texture. When two green mushrooms are obtained, a red mushroom appears. If three red mushrooms are obtained, the "good job!" message appears, and the second round of the game starts.

IV. RESULTS AND DISCUSSIONS

To prove the practicality of the game, we received applications from students who attended elementary schools in Seoul, South Korea. We received 45 applications and selected 40 children who met the criteria of this study. The children were diagnosed with ADHD based on the diagnostic criteria of DSM-5 by pediatric psychiatrists and clinical psychologists and had no developmental or psychotic disorders. To exclude the factors caused by low intelligence, we excluded students whose intelligence of K-WISC-III [46] based on the WISC-III [47] was less than 79 points. Additionally, we conducted the ATA [34] with the participants; all of them were at the ADHD level because at least one out of the four variables of omission errors, commission errors, response times, and the standard deviation of the response times was more than 1.5 times the standard deviation (1.5σ) of the mean.

After explaining the purpose and content of the study to the parents and students, 40 high-risk participants who agreed in writing to participate were finally selected, and 20 students each were assigned to the experimental and control groups. We instructed the parents not to use other medications or treatments while playing the game, so there were no other simultaneous medications or treatments as far as we know. After these preparations, the experimental group played the game throughout 15 sessions over 6 weeks. Each session comprised the modes labeled as easy, general, or difficult and required approximately 30 min. The first five sessions, the second five sessions, and the third five sessions had different levels of difficulty, as shown in Table 1. The control group comprised 20 ADHD-diagnosed children as well, but they were not exposed to the game. We conducted visual tests based on ATA and 14 body group tests based on IM before and after the 15 sessions. When all the sessions were completed, the experimental group answered a survey regarding the game. The details of the demographic information for the groups are summarized in Table 2.

The visual examination in ATA uses three different shapes (triangles, squares, circles). The participant should distinguish, for example, a target stimulus comprising a triangle in a square from a non-target stimulus comprising a square or a circle in a square. During the auditory examination in IM, three stimuli are provided, and the target and non-target stimuli should be distinguished and responded to. The participant should perform 14 different exercises, including specific hand and foot movements, and hit a trigger when the regular reference sound can be heard from a headphone. The measured variables consist of omission errors, commission errors, response times and standard deviations of the response times. The omission error refers to the number of times a participant omits to press a button when the target stimulus is presented.

TABLE 2. Statistics of the groups.

Group	Category	Characteristic	Frequency (%)
Experimental	Gender	Male	17 (85%)
		Female	3 (15%)
	Age	8	12 (60%)
		9	3 (15%)
		10	5 (25%)
	ATA	Omission errors (M/SD)	71.7/14.03
		Commission errors (M/SD)	66.3/18.35
Control	Gender	Male	18 (90%)
		Female	2 (10%)
	Age	8	11 (55%)
		9	3 (15%)
		10	6 (30%)
	ATA	Omission errors (M/SD)	71.85/6.05
		Commission errors (M/SD)	67.85/6

The commission error refers to the number of times a button is erroneously pressed when a non-target stimulus emerges. The response time represents the averaged elapsed response time following the unveiling of the target stimulus; the standard deviation reflects the consistency of the response time. From the omission/commission errors, the response times, and their standard deviations, T-scores are calculated, and the suspicion of ADHD symptom arise when one or more of the variables exhibit a T-score of 70 or higher [37].

A. RESULTS

The means of the ATA errors for the experimental and control groups are summarized in Table 3. As shown in Table 3, the omission/commission errors in the experimental and control groups are similar before the experiments (71.7 and 71.85, 66.3 and 67.85, respectively) but differ after the treatments (54.1 and 70.9, 55.3 and 66.4, respectively). In Table 3, the omission/commission errors of the experimental group have decreased significantly, but those of the control group exhibit only a minor change.

TABLE 3. Mean/standard deviations of ATA results pre- and post-game.

Group	Category	M/SD	
		Pre-game	Post-game
Experimental	Omission error	71.7/14.03	54.1/9.63
	Commission error	66.3/18.35	55.3/10.38
Control	Omission error	71.85/6.05	70.9/9.04
	Commission error	67.85/6	66.4/6.68

Table 4 shows a two-way ANOVA of the omission error results regarding the groups and pre/post test times. According to Table 4, the experimental group shows a statistically significant difference before and after the game [$F(1, 38) = 41.357$, $p < .001$]. The game effect in the experimental group is also statistically significant [$F(1, 38) = 33.318$, $p < .001$]. Consequently, a significant difference is observed between the groups after the game [$F(1, 38) = 8.84$, $p < .001$]. This result means that the two groups did not differ before the eye-contact game, but the experimental group showed a significant reduction compared with the control group after the game.

TABLE 4. ANOVA results of omission errors in Table 3.

Source	SS	dF	MS	F	p
(Intragroup)					
Test time	1720.512	1	1720.512	41.357	.000***
Test time×group	1386.113	1	1386.113	33.318	.000***
Error	1580.875	38	41.602		
(Intergroup)					
Group	1436.513	1	1436.513	8.84	.005**
Error	6173.475	38	162.460		

SS: Sum of Squares, dF: Degree of Freedom, MS: Mean Square, *p <.05, **p <.01, ***p <.001

Table 5 shows the commission error results of a two-way ANOVA based on the groups and the pre/post test times. As shown in Table 5, the experimental group exhibited a statistically significant difference before and after the game [$F(1, 38) = 12.361$, $p < .001$]. The game effect in the experimental group was also statistically significant [$F(1, 38) = 7.273$, $p < .01$]. However, no significant difference was observed between the groups after the game [$F(1, 38) = 4.001$, $p > .05$].

TABLE 5. ANOVA results of the commission errors in Table 3.

Source	SS	dF	MS	F	p
(Intragroup)					
Test time	775.012	1	775.012	12.361	.001***
Test time×group	456.012	1	456.012	7.273	.010**
Error	2382.475	38	62.697		
(Intergroup)					
Group	800.112	1	800.112	4.001	.053
Error	7599.275	38	199.981		

SS: Sum of Squares, dF: Degree of Freedom, MS: Mean Square, *p <.05, **p <.01, ***p <.001

Furthermore, we used the IM before and after the treatment both on the experimental and on the control groups; the results are summarized in Table 6. As shown in Table 6, the mean response times decreased significantly in all cases. In particular, the decrease by 35.42 (from 200.51 to 167.09) for the hand of the experimental group is significant when compared with that in the control group, namely, 11.06 (from 193.06 to 182). The decreases for the feet and bilateral cases in the experimental group are 16.02 and 8.05 (234.74 - 218.72, 225.63 - 217.58), respectively, and those in the control group are 17.45 and 0.13 (239.68 - 222.23, 227.58 - 227.45), respectively. Our game does not affect only the feet cases. To analyze the data in more detail, we grouped "1. Both hands" and "14. Repeat both hands" into "Both hands"; "4. Both toes" and "7. Both heels" into "Both feet"; "3. Left hand," "6. Left toe," and "9. Left heel" into "Left side"; and "2. Right hand", "5. Right toe," and "8. Right heel" into "Right side." The decrease of each case is 31.6, 18.12, 17.23, and 20.46, respectively, in the experimental group. In the control group, the decreases corresponds to 5.47, 18.45, 16.1, and 19.67, respectively. Table 7 shows the results of the T-test analysis of the experimental group in Table 6. Table 7 shows the statistically significant differences ($p < .05$) in the hand,

TABLE 6. **Mean/standard deviations of response times in IM both pre- and post-game in milliseconds.**

Group	Category	Exercise	M±SD	
			Pre-game	Post-game
Experimental group	Hands	1. Both hands	194.65 ± 39.88	166.75 ± 28.99
		2. Right hand	203.1 ± 56.26	162.65 ± 30.29
		3. Left hand	201.8 ± 56.67	171.75 ± 30.28
		14. Repeat both hands	202.5 ± 52.48	167.2 ± 25.22
		Mean	200.51 ± 51.32	167.09 ± 28.7
	Feet	4. Both toes	248.95 ± 54.16	222.45 ± 43.03
		5. Right toe	218.2 ± 46.38	213.95 ± 42.34
		6. Left toe	221.4 ± 26.25	211.9 ± 27.38
		7. Both heels	220.05 ± 59.49	207.3 ± 47.62
		8. Right heel	232.35 ± 58.22	215.65 ± 54.25
		9. Left heel	219.55 ± 39.87	207.4 ± 31.92
		12. Balance right foot	259.1 ± 43.17	232.8 ± 35.95
		13. Balance left foot	258.35 ± 62.29	235.3 ± 44.29
		Mean	234.74 ± 48.73	218.34 ± 40.85
	Bilateral	10. Right hand/left toe	218.15 ± 42.25	213.25 ± 33.65
		11. Left hand/right toe	233.1 ± 50.52	221.9 ± 41.08
		Mean	225.63 ± 46.39	217.58 ± 37.37
	Mean		224.13 ± 49.14	203.80 ± 36.88
Control group	Hands	1. Both hands	193.65 ± 30.07	177.55 ± 34.17
		2. Right hand	202.25 ± 31.02	185.15 ± 20.77
		3. Left hand	206.6 ± 33.36	190.3 ± 16.64
		14. Repeat both hands	169.85 ± 20.06	175 ± 23.5
		Mean	193.09 ± 28.63	182 ± 23.77
	Feet	4. Both toes	227.9 ± 43.04	206.05 ± 25
		5. Right toe	220.8 ± 27.49	213.6 ± 17.7
		6. Left toe	235.6 ± 23.58	226.35 ± 22.95
		7. Both heels	246.75 ± 40.63	231.8 ± 24.68
		8. Right heel	234.1 ± 40.52	223.2 ± 27.88
		9. Left heel	248.55 ± 31.96	225.7 ± 23.09
		12. Balance right foot	261.1 ± 38.64	229.45 ± 30.79
		13. Balance left foot	242.6 ± 54.91	221.65 ± 38.73
		Mean	239.68 ± 37.6	234.21 ± 26.35
	Bilateral	10. Right hand/left toe	237.2 ± 37.21	238.35 ± 23.25
		11. Left hand/right toe	215.95 ± 43.82	216.55 ± 26.76
		Mean	226.58 ± 40.52	227.45 ± 25.01
	Mean		224.63 ± 35.45	218.33 ± 25.42

feet, both hands, both feet, left side, right side, and bilateral cases both before and after the game.

In addition to the quantitative data analyses with both the ATA and IM tests, we conducted user experience surveys with the participants in the experimental group after all the sessions were completed. Because we excluded students with low intelligence in the experimental group, the intelligence of all the participants was within the normal range even with ADHD, and most of them could understand spoken and written instructions. In cases where participants could not understand instructions and they asked questions about the instructions in the survey, we explained the issue until the instructions were clear to them. The survey primarily was in two parts: sixteen questions about motion sickness (from SSQ questionnaires [49]) and nine questions regarding the

TABLE 7. **T-test results of IM in Table 7.**

	N	Time	M ± SD	t	p
Hand	20	Pre	200.51±50.90	7.783	.000***
		Post	167.09±28.40		
Feet	20	Pre	234.74±51.75	5.716	.000***
		Post	218.72±51.75		
Both Hand	20	Pre	198.58±46.18	5.758	.000***
		Post	166.98±26.82		
Both Feet	20	Pre	234.50±58.03	3.777	.001***
		Post	216.38±45.73		
Left Side	20	Pre	214.25±42.98	4.541	.000***
		Post	197.01±34.54		
Right Side	20	Pre	217.88±54.30	3.023	.004**
		Post	197.41±49.35		
Bilateral	20	Pre	225.62±46.59	2.721	.010*
		Post	217.57±37.32		

experience with the game (from SUS questionnaires [50]). The participants were required to select one of four answers for the questions related to motion sickness. The first selection is the strongest positive (sick), and the fourth selection is the strongest negative (not sick). In addition, we gave the participants another questionnaire section regarding their gaming experience. This second questionnaire section comprised nine questions, and the participants were required to choose one answer from five-scale choices for seven of the questions and to write their opinions for the two remaining open-ended questions. In the answers, the first scale choice refers to the worst experience and the fifth scale choice refers to the best experience. The questions and average scores are summarized in Table 8.

Overall, all 20 participants provided negative answers in the sickness surveys. This indicated that they did not experience any sickness during the game. Only one participant answered positively to the question, "My head became heavy. (Fullness of head)." This answer could be attributed to the weight of the HoloLens. In terms of the gaming experience, all 20 children gave an above average score of 3.00. These results mean that the participants enjoyed the treatment that was in the form of a game. Regarding the open-ended questions requiring written answers, most of the respondents indicated that the game was interesting.

B. DISCUSSIONS

This study suggests that our developed eye-contact game can be used as a treatment tool to target the inattention and impulsivity of children with ADHD. Although the game can help reduce both inattention (omission error) and impulsivity (commission error), as shown in Table 3, it appears to be more effective for the former. As shown in Table 3, the decrease in omission error (17.6 (71.7 - 54.1)) is larger than that in commission error (11 (66.3 - 55.3)). This outcome indicates that our game is more effective in improving attention than in reducing impulsivity, based on the fact that the omission errors measure inattention, and the commission errors measure impulsivity [34], [48]. Overall, the participants with ADHD within the experimental group were in the normal

TABLE 8. Questionnaires and mean results.

Category	Question	Score
Sickness	I felt that the game was inconvenient. (General discomfort)	1.15
	I was fatigued during the game. (Fatigue)	1.05
	I had a headache during the game. (Headache)	1
	My eyes became tired during the game. (Eyestrain)	1.15
	I had difficulty in focusing. (Difficulty in focusing)	1.35
	I had saliva in my mouth. (Increased salivation)	1.1
	I was sweating. (Sweating)	1.25
	I became nauseous. (Nausea)	1
	I had a difficult time concentrating. (Difficulty in concentrating)	1.05
	My head became heavy. (Fullness of head)	1.45
	My vision became blurred. (Blurred vision)	1
	I felt dizzy with my eyes open. (Dizzy with eyes open)	1.05
	I felt dizzy with my eyes closed. (Dizzy with eyes closed)	1
	I felt that the ceiling was rotating. (Vertigo)	1.05
	I had a stomachache. (Stomachache)	1
	I burped. (Burping)	1.15
Game experience	Did you concentrate on the game?	4.8
	Did you feel that the difficulty of the game was appropriate?	4.45
	Did you think that the game was interesting?	4.55
	Did you feel that the partner is in front of you?	4.65
	Did you watch the partner's face during the game?	4.85
	Did you think that the game helped to stare at the people?	4.8
	Do you want to play the game again?	4
	What did you like about the game? Is there anything that helped you?	
	Are there any disappointments or improvements in the game?	

range in all cases owing to the therapeutic effects of the game, considering that the ADHD suspicion range must be over 70 for one of the variables. By contrast, the participants within the control group were still in the ADHD suspicion range. In addition, the mean response time for the IM decreased with improved attention, as shown in Table 6.

In Section IV-A, we described the quantitative and qualitative results of the game. Although the results were satisfactory, the game could be further improved as follows. First, eye-tracking devices are required to correctly detect the participant's eye movements. Currently, the HoloLens does not support eye-tracking functions; therefore, our game attempts to detect a match between the face outline and the partner's face by head-movement tracking. Next, more games should be developed to provide more choices/options for ADHD children, as they may easily lose interest when they play only one type of game. Subsequently, the effects of the developed game should be compared with other treatment methods, such as medications and therapies. Next, our game focuses on improving visual attention through eye-contact processes. Considering that the IM focuses on auditory attention, a treatment including both our game and the IM may render a greater impact on ADHD children. In our opinion, this combination is worth investigating.

V. CONCLUSION

Recently, the number of children with ADHD has increased significantly, and it is expected to further increase in the future. This trend is concerning, as ADHD can result in difficulties in childhood academic and social development that extend into adulthood. To adequately treat the children with ADHD without medications or therapists, we investigated and developed a mixed realty (MR)-based game that could be readily used to treat ADHD children at home. To create an enjoyable treatment that also motivates ADHD children, we used a game and designed the game levels and specific sound effects based on each level and added a leaderboard. Furthermore, we verified the effectiveness of the treatment using ATA, IM, and surveys. Inattention and impulsivity improved significantly based on a statistical analysis of the results. To the best of our knowledge, this work is one of the first attempts to use an MR HMD (mixed reality head-mounted display) treatment for ADHD, and we proved its effectiveness on children clinically diagnosed with ADHD. In the future, we plan to improve the game with a real eye-tracking device and develop additional games to appropriately treat ADHD children. This improved game will be compared with other treatments, and other tools will be investigated.

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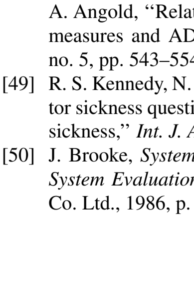

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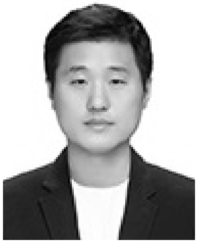

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