Game-Based Social Interaction Platform for Cognitive Assessment of Autism Using Eye Tracking

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***Abstract*—The design goals of recently developed serious games are to improve attention, affective recognition, and social interactions among individuals with autism. However, most previous studies on serious games used behavioral questionnaires to evaluate their effectiveness. The cognitive assessment of individuals with autism after behavioral intervention or drug treatment has become important because it provides promising biomarkers to assess improvement after cognitive intervention. In this study, we developed a game-based social interaction platform incorporating an eye-tracking system for children and preadolescents with autism. Three modules (focusing on gaze following, facial emotion recognition, and social interaction skills) are included in the platform; participants with autism learn these according to their cognitive abilities. The eye-tracking results showed decreased fixation durations when autistic children looked at positive emotional expressions and focused on multiple targets. Prolonged saccade durations and shorter fixation times for social-related facial emotion expressions were also found in preadolescents and teenagers with autism. Our findings suggest that these atypical gaze patterns are reliable biomarkers for evaluating the social and cognitive functions of autistic individuals while playing serious games. The proposed platform's game-based modules and the findings regarding aberrant gaze patterns in autistic individuals demonstrate the possibility of evaluating cognitive functions and intervention effectiveness by using eye-tracking signals in a serious game or real-life environment.**

***Index Terms*—Social interaction game, autism spectrum disorder, eye tracking, serious games.**

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I. Introduction

Autism spectrum disorder (ASD) is classified as a neurodevelopmental disorder according to the Diagnostic and Statistical Manual of Mental Disorders Fifth Ed. (DSM-5) [1]. Previous studies have suggested an impairment of facial processing and recognition in ASD; this also affects the individual's ability to express emotions [2], [3]. Impairment of facial processing and emotional expression may produce a deficit in social cognition. Recent studies suggest that both the impairment of social motivation and the deficit of basic perception produces difficulties in social interaction for individuals with ASD [3], [5]. ASD has been widely recognized as a developmental disorder of psychogenic origin; thus, both genetic and environmental factors are involved across multiple brain networks. Neuroimaging studies also suggest that ASD is a connectivity disorder, producing an altered development, anatomy, and functionality [6], [9]. Early interventions and cognitive assessments based on developmental and neuroimaging findings are required to quantitatively evaluate the social and cognitive functions of autistic children.

The development of game-based training platforms for behavioral interventions has emerged as a growing trend, because individuals with autism are commonly reported to enjoy using computer technology with highly predictable and affect-free interfaces [10]. In the past decade, numerous serious games have been developed for personalized training and the cognitive assessment of emotions, social interactions, and daily living skills [11], [14]. Different aspects of training have been developed, including affective, behavioral, and cognitive functions, as well as social skills [14]. It has been shown that the role-play or single-player modes of these games offer powerful tools for intervening in emotional recognition and social skills [15], [16]; this has been demonstrated in Fearnot [17], the ECHOES project [18], JeStiMulE [19], GOLIAH [20], ALTRIRAS [21], and SSIT [22]. Multiplayer [23], [24] and virtual reality (VR) [25], [27] game modes have also been introduced in the past few years and have exhibited comparable performances. These results indicate the effectiveness of assistive technologies involving game-like interactions.

Although the aims of these game-based platforms are to improve attention, affective recognition, and social interaction, most previous studies have used behavioral questionnaires or oral reports to evaluate game effectiveness. With the advanced development of human–machine interfaces, physiological signals such as touching, eye-tracking, heart-rate variability, and electroencephalography (EEG) are essential for the future implementation of game-based interfaces, to further investigate the underlying mechanisms and effective biomarkers. Challenges remain when implementing certain neurofeedback platforms, owing to the inconvenient and uncomfortable design of wearable sensing devices, especially when measuring physiological signals from children with autism. Mobile and easy-to-set devices are essential for certain types of studies. Among these physiological signal-sensing devices, eye-tracking systems can remotely record gaze locations using infrared technology; this represents a more feasible approach for the cognitive assessment of autistic children, compared to other neuroimaging techniques. Gaze behavior and attention allocation have long been known to be altered in autistic individuals [28], [32]. Reduced attention to the eyes, mouth, and face and increased attention to the body and non-social elements have been consistently reported; these can be seen as reliable biomarkers in ASD [29]. According to the feasibility of eye-tracking modalities, recently developed game-based interfaces for ASD have incorporated gaze location information when assessing intervention or cognitive functions [24], [27], [33], [34]. Although a few studies have introduced the possibility of using eye-tracking signals in serious games as biomarkers for cognitive assessment, a few critical factors that influence the generalization of these biomarkers remain, such as the variety of tasks (or stimuli), participant age, and cultural differences. Further investigation is required to explain these diverse results across different tasks, as well as the ages and nationalities of participants. The reliability of gaze patterns as biomarkers of ASD assessment should also be verified. The potential of eye-tracking technology and its translation into practical benefits for the diagnosis, intervention, and cognitive assessment of individuals with ASD represents a significant research gap that needs to be bridged.

In this study, we developed a game-based social training interface for children and preadolescents with autism. The interface includes several interaction games with different modules for autistic participants to learn, depending on their age and cognitive function. These modules focused upon gaze following, facial emotion recognition, and complex social interaction skills; they were implemented with real-life scenes and time-synchronized with an eye-tracking system. Gaze locations and regions of interest were recorded and analyzed to identify possible biomarkers for cognitive assessment. In our previous studies [4], [5], we showed that both joint attention and basic gaze perception deficits may hamper the development of social cognition in ASD patients. The results of the present study show that children and preadolescents with autism have altered fixation and saccade durations in response to emotional and social elements when playing social training games. The development of these game-based modules and their findings may offer promising biomarkers for evaluating cognitive functions and the effectiveness of interventions in real-life environments.

II. Materials and Methods

A. Participants

We recruited 48 participants, comprising 30 typically developing (TD) children and 18 autistic children. All children with autism were recruited from the National Taiwan University Hospital and were diagnosed according to the diagnostic criteria of the DSM-5 and International Classification of Diseases (ICD-10; World Health Organization, 1994). Participants were divided into two groups according to their age and the games that were suitable for them to learn and play. The first group included 30 toddlers and children with 12 autistic children (aged 4.75 ± 1.76; three boys) and 18 TD children (aged 4.89 ± 1.24; 12 boys). We excluded five children with autism from the final sample because they did not pay attention to the stimuli on the screen or refused to complete the calibration process for the eye-tracking experiment. The second group included 18 preadolescents and teenagers, comprising 12 TD adolescents (aged 11.83 ± 1.27; seven males) and six autistic participants (aged 13.83 ± 3.71; four males).

This study was approved by the Research Ethics Committee of National Taiwan University Hospital, Taiwan (REC no. 201709023RIPD). All legal representatives provided written informed consent prior to the experiment. None of the participants had comorbid major neuropsychiatric disorders such as epilepsy, organic mental disorder, bipolar disorder, or schizophrenia. The verbal and performance intelligence quotients (IQs) of the toddlers and children were assessed using the Weschsler Intelligence Scale for Children [35] or the Weschsler Preschool and Primary Scale of Intelligence [36], [37]. Preadolescents and teenagers completed neuropsychological tests of nonverbal abilities, the Test of Nonverbal Intelligence, Fourth Edition (TONI-4), to measure their abstract reasoning and problem-solving capabilities [38].

B. Development of Game-Based Social Training Platform

The platform included three interaction games with designed rewards and different topics (gaze following, facial emotion recognition, and complex social interaction skills) for autistic participants to learn. The interacting games (or stimuli) were also designed with real-life scenes and categorized into events to fit the criteria for an eye-tracking experimental paradigm. Unity 3D was used to develop the games and was time-synchronized with the eye tracker. The platform was divided into three modules with role-playing operating modes, as shown in Fig. 1. In the first module, a gaze-following game was proposed, including the basic techniques of joint attention. Emotion recognition tasks (e.g., facial expressions, emotion matching, empathy, and matching-pair memory) were included in the second module. The third module integrated the previous two and used role-playing scenarios to imitate social interactions closely resembling real life. Rewards, such as stickers or toys, appropriate to the ages and preferences of the participants, were offered in the game. The recruited participants undertook one or two suitable modules, depending on their age and IQ score. Demonstration videos are available on https://reurl.cc/WqrYox.

1) Module 1. Joint-Attention Game: A joint attention game was designed specifically for autistic toddlers and children aged 2–7 to evaluate their gaze-following and joint attention abilities. The joint attention game was divided into discrete events to fit the criteria for an eye-tracker-compatible experimental paradigm. The game aimed to evaluate the participants' eye contact and gaze-following abilities, which are basic activities involved in recognizing facial expressions and initiating joint attention during social interactions. In the beginning of the game, the participants were instructed to choose a character they wished to play. In each trial, the participants were instructed to make eye contact with a cartoon character on the screen (*eye-contact condition*) and judge which flavor of ice cream the cartoon character preferred, based on its gaze direction (*gaze-following condition*, Fig. 2A). The complexity of the game was manipulated by varying the number of cartoon characters on the screen, using single or multiple targets. All the instructions were voiced without captions by women. The voice instructions and sound effects were designed for toddlers and children. Participants' behavioral and eye-gaze responses under these conditions were analyzed accordingly.

2) Module 2. Emotion-Recognition Game: The emotion-matching game was an interactive computer game with a displayed cartoon character performing a non-player character role. The utilization of cartoon characters increases ASD toddlers' and children's willingness to participate in the game; meanwhile, photographs help them learn facial emotion expressions in real-world situations. The game lasted for 10 minutes and was designed specifically for toddlers with ASD and children aged 2–7. There were four types of basic facial emotion expressions in the game: happy, sad, surprised, and angry. Three conditions were presented in the game: (1) Emotion matching: The participants were requested to click the corresponding emotion under different scenarios. (2) Empathy: Participants were requested to drag the face with the correct emotional expression of the character. (3) Matching-pair memory game: Participants memorized the facial emotion expressions and matched faces with the same emotional expressions, as illustrated in Fig. 2B. The complexity of the memory game increased when the participants learned more facial emotion expressions. All the instructions were voiced by women. The voice instructions and sound effects were designed for toddlers and children. A few of the complicate instructions were also given with Chinese captions.

3) Module 3. Social Interaction Game: The social interaction game was designed with different social topics and scenarios for ASD preadolescents and teenagers to learn facial-emotion recognition and social interaction skills. Cartoon characters designed with animation styles based on the preferences of East Asian teenagers increased their willingness to participate in the game. The game-based interface was divided into two conditions, with different operating modes. In the first condition, a complex version of the facial emotion recognition game was proposed, including basic techniques of facial expression recognition and attention sharing, using ten cartoon characters of different ages and genders. The second condition integrated the first condition with role-playing and first-person scenarios to imitate real-life social interactions, as shown in Fig. 2C. Rewards, such as vouchers, appropriate to the ages and preferences of the participants were offered at the end of the game. The resulting social training game was a 30-minute individual interactive computer game, including 84 facial emotion recognition trials and 45 social behavior selection trials, with triggers communicated via a lab streaming layer to facilitate synchronization with the eye-tracking system. Each trial included a 12-second description of each scenario. Then, the participants were instructed to make eye contact with a character on the screen and select the correct facial emotion expression for the social situation (1–3 s). Finally, the participants were asked to select an appropriate behavior or reaction, according to the social behaviors of the character (7–10 s). All the instructions of this module were displayed on the screen with no voices or sound effects.

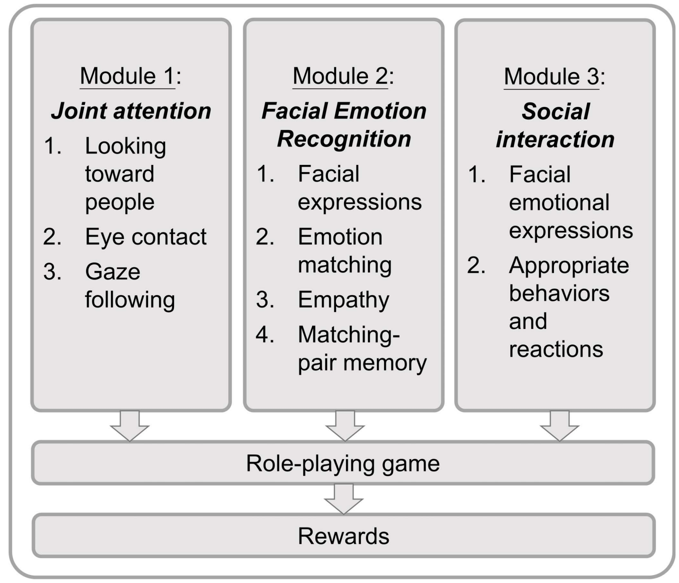

Fig. 1. Structure of the proposed social interaction platform in this study.

C. Experimental Setup and Eye-Tracking Signals

The gazing points of the participants were recorded using the Tobii X2-30 eye-tracking system (Tobii Technology, Inc.), which is a remote-based eye-tracker that utilizes the pupil center corneal reflection technique. The Tobii eye-tracking system is one of the most widely used devices for studying the pupillometry of ASD [39]. The accuracy and precision of the Tobii X2-30 eye-tracker have already been estimated by other researchers [40]. The timestamps of the eyes and the x and y coordinates of the gazing locations were recorded and sampled at a frequency of 30 Hz. The eye-tracking system was interfaced with a laptop installed with Tobii Pro Studio software and attached to the bottom of a 16-in portable monitor via a magnetic bracket that held it in place. Five-point calibration of the pupillary gaze direction was performed using the Tobii Studio Professional calibration instrumentation verification program at the start of each testing module. Participants were asked to sit on a chair in front of the viewing monitor. The interactive games described above were presented on the screen; the distance between the participants and the screen was no longer than 80 cm, and the freedom of head movement was less than 50 cm $\times$ 36 cm. When the

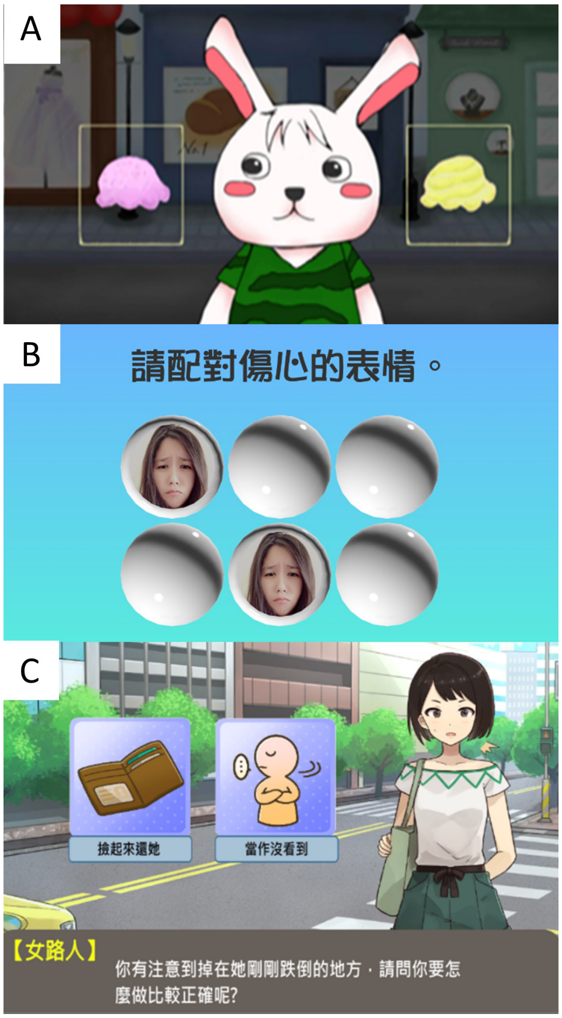

Fig. 2. Proposed social interaction games, including the (A) gaze-following module, (B) emotion-recognition module, and (C) social training module.

stimuli were presented, the reflection of near-infrared light from the cornea and pupil was measured.

Tobii Pro Studio software was used to preprocess the raw eye-tracking data. Fixations and saccades were defined using the standard built-in fixation filter of the software, which automatically interpolates segments of missing data shorter than 60 ms. A velocity threshold of 30 °/s was applied. The specified areas of interest (AOIs) were defined on each frame of the stimuli to facilitate subsequent statistical analysis of the eye-tracking data. For the first game module (gaze following), the AOIs located in the game screen and the eyes, target (correct answer) regions, and non-target (wrong answer) regions were drawn, as shown in Fig. 3. The AOIs of the game screen, targets, and non-targets were defined as squares along the borders of objects designed with equal areas. The AOIs of eyes were defined 2 cm away from the upper and lower edges of the eyes and the left and right margins of the faces from different cartoon characters. For the second game module (facial emotion recognition), the AOIs of the four types of facial emotion expressions (happy, sad, angry, and surprise) were defined as circles along the borders of the objects illustrated in Fig. 4. The AOIs of the third game module (social training) were more complex. In the first condition of emotion recognition in Module 3, five AOIs were defined, namely eyes, lips, facial expressions of correct and wrong emotional expressions, and the entire game screen (Fig. 5). In the second condition of social interaction in Module 3, seven AOIs were defined, namely the facial emotional expressions of the cartoon characters, appropriate behaviors and captions, inappropriate behaviors and captions, descriptions of each scenario and question, and the whole game screen (Fig. 6). The areas of facial emotional expressions were defined as ovals with an upper margin fitted to the hairs of distinct cartoon characters. All the other AOIs in this module were defined as squares or rectangles along the borders of the objects, with equal areas for comparable objects.

Eye-tracking metrics were exported from the software for further analysis. Six main parameters were used: total fixation duration, saccade duration, time to first fixation (TTFF), first fixation duration (FFD), average fixation time (AFT), and average saccade time (AST). The total fixation duration (TFD) of an AOI represents the sum of the time intervals for each fixation, which are defined as the period in which the eyes hold the central fovea vision in place. The total saccade duration (TSD) of an AOI represents the summed durations of each saccade, which is a form of eye movement used to move the fovea from one target to another. The TTFF and average first fixation duration (AFFD) are the times elapsed between the beginning of each trial and the first fixation of an AOI and its duration, respectively. The AFT and AST are the mean fixation and saccade times calculated from the valid trials of each condition. Statistical analysis was then performed to compare ASD and TD participants. The Wilcoxon signed-rank test was used to assess the differences between the two groups using the six parameters of the AOIs defined in each game module.

III. Results

A. Task Performance

All TD and ASD toddlers and children were within normal IQ categories (full-scale IQ $\geq$ 70). Participants of each module with a level of completeness lower than 70% or missing data of the eye-tracker higher than 30% were excluded from further statistical analysis. In Module 1, 17 TD and 7 ASD toddlers and children were included for further analysis. In Module 2, only 14 TD and 3 ASD toddlers and children were included in the final statistical analysis, owing to the increased difficulty of the task. The mean accuracy rates of the joint attention game (Module 1) for TD and ASD children were 98 $\pm$ 4% and 90 $\pm$ 2%, respectively, with no discernible difference ($p = 0.300$). The mean reaction time of the autistic children was 6.66 $\pm$ 2.65 s, which is marginally slower than that of TD children (6.20 $\pm$ 2.01 s); however, the difference was insignificant ($p = 0.750$). The mean reaction time of the emotion-recognition game (Module 2) for TD and ASD children were 5.61 $\pm$ 3.98 and 5.61 $\pm$ 3.07 s, respectively, with no significantly observable difference.

All the recruited 12 TD and 6 autistic preadolescents and teenagers were able to play the designed social interaction

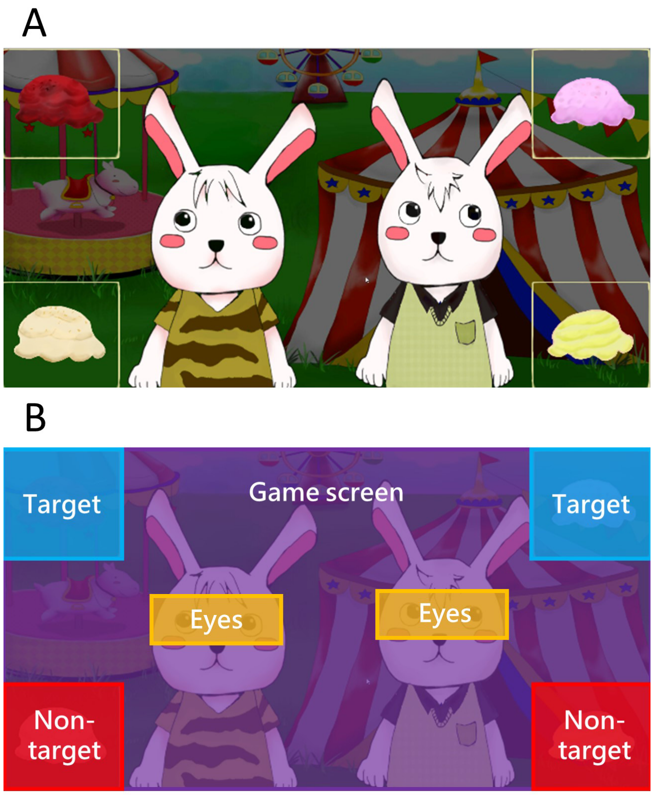

Fig. 3. (A) Game screen and (B) AOIs of the gaze-following module, including targets (correct answers), non-targets (wrong answers), eyes, and the entire game screen.

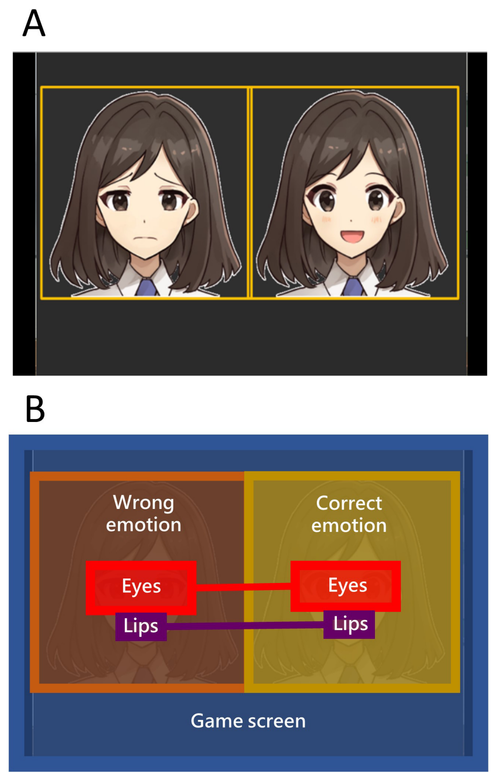

Fig. 5. (A) Game screen and (B) AOIs of the first condition of social training module, including eyes, lips, facial expressions of correct and wrong emotional expressions, and the entire game screen.

Fig. 4. (A) Game screen and (B) AOIs of the emotion-recognition module, including the AOIs for the four types of facial emotion expressions.

game (Module 3). The mean scores on the TONI-4 nonverbal ability test for TD and ASD participants were 115 ± 15 and 105 ± 17, respectively; no significant difference was observed between the two groups ($p = 0.417$). The mean reaction time of the social interaction game for autistic participants was 4.23 ± 1.17 s, which is marginally slower than that of TD (3.64 ± 1.39 s), with no significantly observable difference ($p = 0.400$). The mean accuracy rates were $98 \pm 2\%$ and $94 \pm 9\%$ in the TD and ASD participants, respectively, and no significant difference was observed between the two groups ($p = 0.195$).

B. Eye-Tracking Data

The gaze locations of the participants were recorded and analyzed. The specified AOIs were defined on each frame of the three modules, to facilitate subsequent statistical analysis of the gaze locations. No significant difference was observed between the two groups for the TFDs of the whole game screen in all the three games, which indicated the validity of the comparison results calculated from other AOIs. The results of the joint attention game (Module 1) are shown in Fig. 7. The six parameters of the AOIs for a single target, multiple targets, and eyes with single or multiple characters were compared. ASD toddlers and children showed decreased attention to the targets when gaze-following cartoon characters. In the single-target gaze-following condition (Fig. 7A), the AFFD of targets in TD children was 3.42 ± 0.33 s, which is higher than that of ASD children (2.42 ± 0.37 s), with no discernible difference ($p = 0.066$). The AFFD of non-target in TD children (0.18 ± 0.06 s) was also higher than

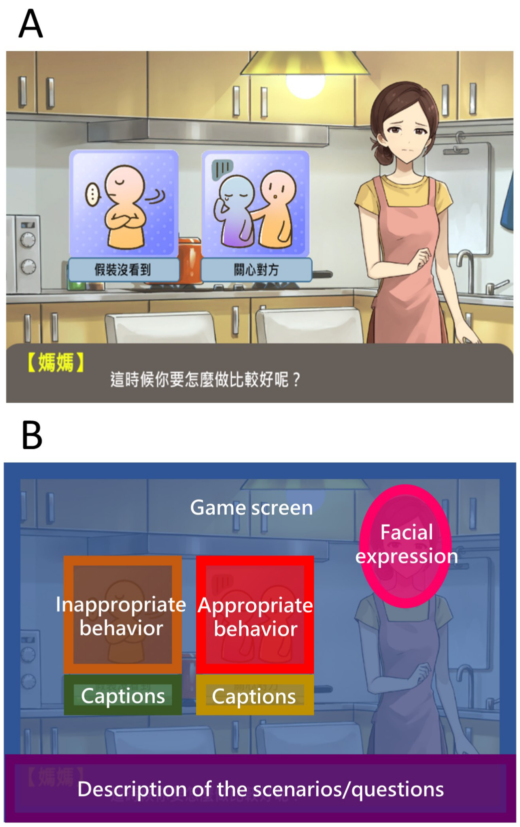

Fig. 6. (A) Game screen and (B) AOIs of the second condition of social training module, including facial expressions, appropriate behaviors and captions, inappropriate behaviors and captions, descriptions of each scenario and question, and the entire game screen.

that of ASD children (0.13 ± 0.08 s) in this condition, with a significantly observable difference ($p = 0.042$). The results also indicated that children with ASD spent less time (5.47 ± 1.68 s) looking at the eyes of a single cartoon character compared to TD children (8.68 ± 0.96 s); however, no pronounced difference was observed between the two groups ($p = 0.065$). The comparison of single- and multiple-target conditions is illustrated in Fig. 7B, the TFD of TD children was 16.10 ± 1.07 s in the single-target gaze-following condition, which is subtly higher than that of ASD (15.08 ± 1.82 s), with no discernible difference ($p = 0.799$). For the multiple-target gaze-following condition, the TFD of TD participants (20.32 ± 2.18 s) was significantly longer ($p = 0.042$) than that of ASD children (14.33 ± 1.73 s).

For the emotion-recognition game (Module 2), no significant differences were observed in any of the six parameters, except for the TFDs of the AOIs for the four facial emotional expressions (Fig. 7C). The average TFDs were longer in TD children than ASD ones for three types of facial emotion expressions: happy (TD: 44.17 ± 4.13 s; ASD: 29.90 ± 7.52 s), sad (TD: 45.74 ± 5.18 s; ASD: 41.56 ± 3.24 s), and surprise (TD: 38.28 ± 9.26 s; ASD: 26.27 ± 7.29 s). A pronounced difference was observed only for happy facial expressions ($p = 0.047$). For angry facial expression, ASD children spent longer (40.64 ± 9.75 s) looking at the faces than TD participants (38.46 ± 7.29 s), with no discernible difference.

The TFDs, TSDs, TTFFs, AFFDs, AFTs, and ASTs were recorded and analyzed as the participants played the social interaction game (Module 3). In the first condition of Module 3 (facial emotional recognition), the AFTs of eyes were significantly shorter for the ASD preadolescents than those of TD (TD: 610 ± 382 ms; ASD: 243 ± 162 ms; $p = 0.025$), as indicated in Fig. 8A. In contrast, the AFTs of lips in both correct and incorrect emotional expressions were higher in the ASD preadolescents (TD: 66 ± 70 ms; ASD: 274 ± 300 ms), with no significance observed ($p = 0.067$). Subtly longer TTFFs of eyes (TD: 254 ± 110 ms; ASD: 414 ± 186 ms; $p = 0.067$) and shorter AFFDs of correct emotional expressions (TD: 226 ± 94 ms; ASD: 154 ± 87 ms; $p = 0.083$) were also observed in the ASD participants (Fig. 8B). In the second condition of Module 3 (social interaction), the TFDs were longer for TD than ASD participants for all game-related AOIs (Fig. 9A), including the icons of appropriate behaviors (TD: 19.18 ± 4.06 s; ASD: 10.89 ± 3.83 s), inappropriate behaviors (TD: 13.73 ± 2.95 s; ASD: 9.32 ± 1.98 s), and facial emotion expressions (TD: 4.50 ± 1.29 s; ASD: 1.00 ± 0.55 s). Among the AOIs relating to social interactions, a significant difference in TFDs and was observed only for facial emotion expressions ($p = 0.024$), as well as the AFTs (TD: 105 ± 100 ms; ASD: 23 ± 30 ms; $p = 0.018$). The AFFDs regarding the FFDs of facial emotional expressions were also shorter in ASD, with no significance (TD: 72 ± 74 ms; ASD: 19 ± 28 ms; $p = 0.066$). The saccade durations were also analyzed when the participants read descriptions of the game scenarios. As illustrated in Fig. 9B, the results revealed that the average TSDs were longer for ASD preadolescents and teenagers than TD ones when the participants read the captions for appropriate (TD: 0.51 ± 0.15 s; ASD: 1.03 ± 0.43 s) and inappropriate (TD: 0.43 ± 0.11 s; ASD: 0.58 ± 0.22 s) behaviors and the descriptions of scenarios and questions (TD: 0.48 ± 0.16 s; ASD: 1.44 ± 0.40 s). A pronounced difference in TSD was observed between the two groups when the participants read the descriptions of the questions or game scenarios ($p = 0.018$), as well as the ASTs of the descriptions of scenarios and questions (TD: 11 ± 13 ms; ASD: 35 ± 25 ms; $p = 0.014$).

IV. Discussion

The aim of this study was to develop a game-based social interaction training platform for ASD children and teenagers and to propose quantitative biomarkers for their cognitive assessment, using eye-tracking signals. A social interaction platform was implemented with three modules of different topics for children and teenagers with ASD, which focused on the topics of joint attention, emotion recognition, and social interaction. Aberrant gaze patterns were identified in both ASD children and teenagers when they played social interaction games. First, ASD children spent less time viewing positive emotion expressions than TD children during emotion recognition. When multiple targets were present on the screen, autistic children also spent less time focusing on the targets than TD participants. In a more complex social interaction

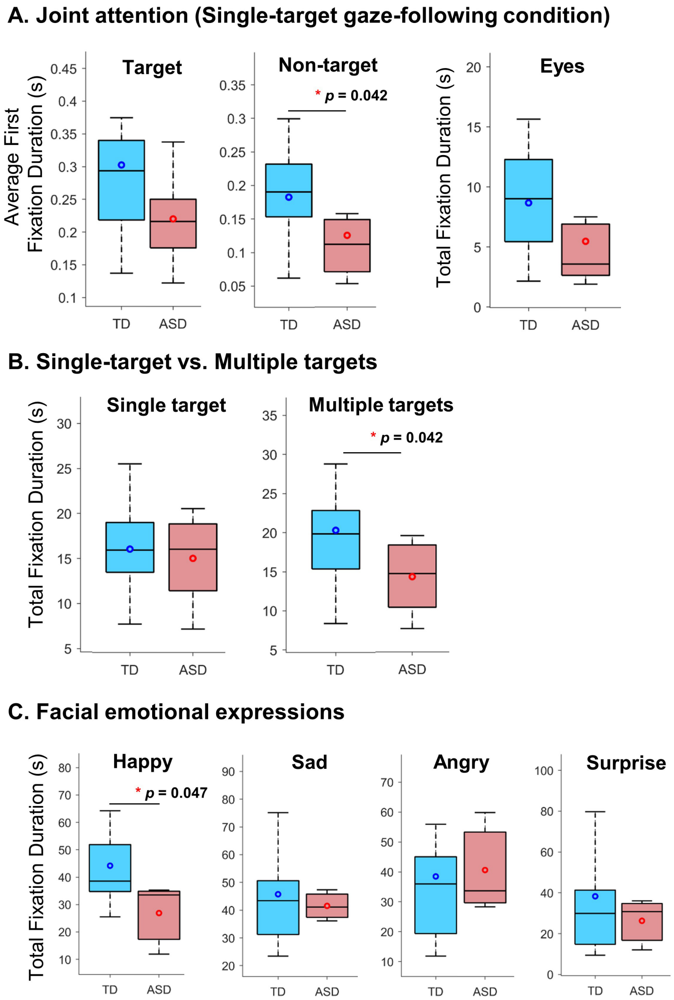

Fig. 7. Average first fixation duration (AFFD) and total fixation duration (TFD) of (A) the AOIs of targets, non-targets, and characters' eyes in the single-target gaze-following condition, and (B) comparison of single- and multiple-target conditions in the joint-attention game. (C) Four types of facial emotion expressions for the emotion-recognition game. Average AFFDs and TFDs are marked as red and blue circles in the figure.

module on the platform, it was found that ASD teenagers spent less time viewing social facial emotion expressions than TD participants. Finally, the saccade durations were found to be increased in ASD participants when they read the descriptions of the scenarios and questions. These findings suggest that eye tracking can be encompassed into a cognitive training system for ASD children and teenagers, to evaluate the performance of the platform and the improvement of participants' cognitive functions, by using gaze locations as biomarkers.

Serious and entertainment games are increasingly being proposed as potential tools for behavioral interventions in individuals with ASD [11], [14]. These games have been developed to improve the cognitive functioning and quality of life of ASD patients [14]. However, several limitations remain in current serious games. The first limitation is that most of these games are developed for high-functioning ASD individuals [12]. In our experience, low-functioning participants may have a problem understanding the contexts, even for games that were designed for their age group. The social interaction platform proposed in this study was designed with three modules containing a variety of cognitive and social functions. Participants were able to attend an appropriate module for their ages and cognitive abilities. Several previous studies have also mentioned this issue and designed platforms with multiple games that target low-level skills [20]. The implementation of a platform with multiple modules and

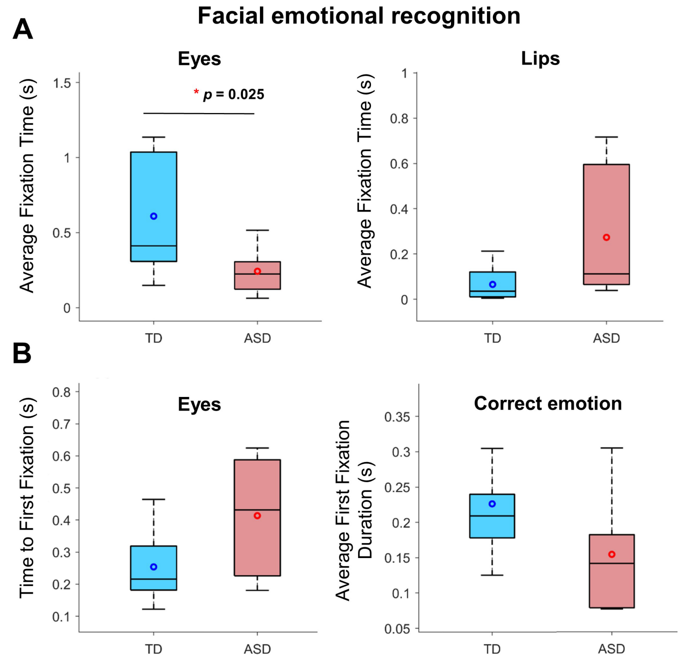

Fig. 8. (A) AFTs for the AOIs of eyes and lips, and (B) TTFFs of the eyes and AFFDs of correct emotional expressions for the condition of facial emotional recognition in the social interaction game. The average values are marked as red and blue circles in the figure.

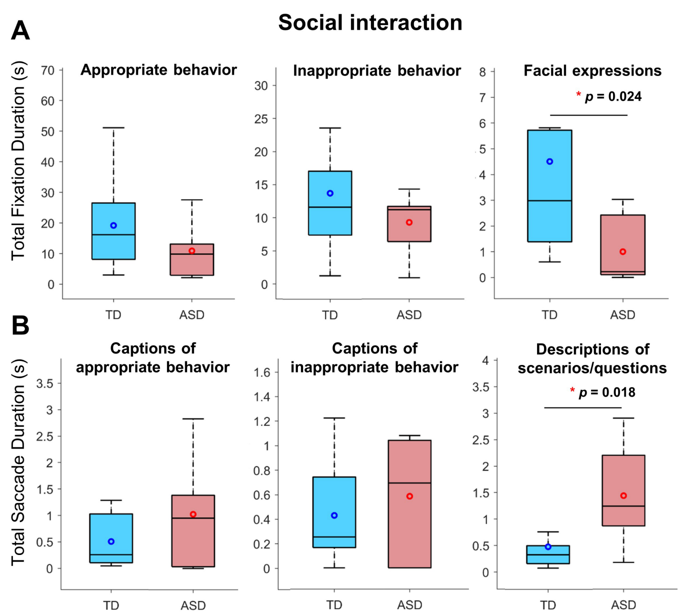

Fig. 9. (A) TFDs for the AOIs of appropriate behaviors, inappropriate behaviors, and facial emotion expressions. (B) TSDs for the captions of appropriate and inappropriate behaviors, as well as the scenario and question descriptions for the second condition of the social interaction game. The average TFDs and TSDs are marked as red and blue circles in the figure.

different levels of game difficulty represents an essential step in making these platforms more accessible to younger children or children with severe autism.

Another issue with the current developmental status of serious games for ASD is the lack of a neurofeedback mechanism for assessing the performance of these platforms. Most previously developed serious games have used questionnaires or oral reports to evaluate the outcome of game intervention [12], [14]. Recent studies have used eye-tracking signals in serious games as possible biomarkers for cognitive assessment [24], [27], [33], [34]. Unlike other neuroimaging techniques such as EEG [41] and functional magnetic resonance imaging [42], an eye tracker can remotely record gaze locations using infrared technology, which is more suitable to serious games platforms for ASD. Atypical gaze patterns have been reported in these studies, which used eye-tracking signals as an index to control serious games or to assess cognitive functioning during game playing [24], [27], [33], [34]. Chukoskie et al. proposed a gaze-contingent game system for behavioral intervention in children and teens with ASD, by allowing them to control the game using gaze patterns. Improved attention orientation and eye movement performances have been observed after training [34]. Babu et al. proposed a multiplayer interaction and a VR platform with gaze tracking functions for individuals with ASD. The eye-gaze results were differentiated between the two groups, and they indicated an underlying relationship between the gaze pattern and task performances of the participants [24]. Jyoti et al. designed a VR and computer-based joint attention task platform for children with ASD. Differentiated implications in task performance and gaze patterns were identified in ASD children when preferred objects were presented as stimuli in a joint attention task [27]. Varma et al. developed a game-based mobile application to identify the social engagement of individuals with ASD. Altered gaze fixation patterns and unique visual scanning patterns were found in ASD (compared with TD) participants [33]. The present study further implemented a social interaction platform with eye-tracking signals, recorded whilst participants were playing games with multiple cognitive topics. Therefore, the gaze locations of ASD and TD participants can be analyzed under different cognitive situations, including gaze following, joint attention, facial emotion recognition, and social interaction. Our results produced findings comparable to those of previous eye-tracking studies for ASD, which verifies the hypothesis that eye-tracking signals may represent a reliable biomarker for validating newly developed serious games.

Although the incorporation of eye-tracking signals in serious games remains underdeveloped, eye tracking has long been understood to offer a reliable index for evaluating social attention in traditional cognitive experiments of ASD [28], [30], [43]. As mentioned earlier, the Tobii eye-tracking system is widely used for studying the pupillometry of ASD [39]. Several researchers used eye-tracking signals to study different cognitive and social functions of ASD, including facial emotional expressions [44], visuospatial orienting [45], emotion-discrimination task [46], reading comprehension skills [47], social images [48], and gaze cue in a face-following task [49]. A decreased fixation duration for social stimuli has been consistently identified in individuals with ASD [29], [43]. Our results show that autistic children demonstrate shorter fixation durations in positive emotional expressions than TD children during emotion recognition, which accords with previous studies in facial emotion expressions [50]. However, this differentiation was not observed for negative facial expressions when the children played the emotion recognition game. It has been noted that the performance of facial emotion recognition in ASD depends on multiple factors, such as IQ, age, task, and type of emotion [51]. Numerous previous studies matched participant groups according to their IQ, and thereby increased the inconsistency of findings by neglecting the effect of the development of emotion recognition abilities in younger children with the same chronological age [51]. Consequently, several studies have claimed that a shorter fixation duration is observed in ASD children both in positive and negative facial emotion expressions [50], whereas others reported no group differences in gaze behavior and reaction time between happiness, sadness, anger, and surprise [51], [52]. Whether a joyful voice accompanied by happy faces motivates TD children but not ASD children is of particular interest. Our results also demonstrate that children with autism spent less time focusing on the targets than TD participants when multiple targets were displayed on the screen. Although it has been reported that ASD individuals tend to focus on only one of the objects rather than exploring the entire image with multiple objects [53], several studies still report no difference in fixation duration between groups when multiple targets are present on the screen [54]. The inconsistent findings of previous eye-tracking studies in infants and young children with ASD were discussed in a systematic review by Mastergeorge et al. [55]. The variability in eye-tracking protocols and the heterogeneity of stimuli used for eye tracking may explain these diverse results [55]. Further investigation is required to clarify the reliability of gaze patterns as biomarkers for young children with ASD.

In contrast, more consistent eye-tracking results have been reported in school-age children, preadolescents, and teenagers with ASD over the past decade [29], [43]. The gaze patterns analyzed from the complex social interaction module of the proposed platform for school-age children and teenagers with ASD illustrated two main findings. First, our results demonstrated decreased fixation duration on social-related facial emotional expressions in individuals with autism compared to TD participants. Previous studies on eye tracking have also reported consistent findings of reduced attention to faces in ASD [29], [43], which suggests the lower accessibility of social information to ASD individuals. The present study further claims that individuals with ASD show a reliable pattern of gaze abnormalities in social-related facial stimuli, even for a complex game screen with multiple objects (Fig. 5); this suggests atypical attention allocation in ASD towards selected socially relevant information. Second, our results show that saccade durations increased in ASD when the participants read the descriptions of scenarios and questions. Based on previous studies, the prolonged saccade duration observed in ASD suggests that the attention and visual orienting systems are relatively spared from the successful shifting of attention to other locations [53], [56].

A major limitation of this study is the small sample size of ASD participants for each module developed on the platform, especially for younger children in the first two game modules. As mentioned, younger children with a severe degree of ASD may have problems understanding games that were designed for their chronological age group. Therefore, it was difficult to match the age distribution between the ASD and TD groups, because the ASD toddlers did not perform at the same level as TD children of the same chronological age. This is also suggested to be one of the main reasons for the inconsistent results reported in previous eye-tracking studies of infants and children with ASD [55]. In contrast, our eye-tracking results in ASD preadolescents and teenagers demonstrated reliable findings aligned with those of previous studies (even with a more complex serious game platform), despite the small sample size.

V. Conclusion

Conventional approaches adopt behavioral questionnaires or oral reports when cognitively assessing ASD via serious games; in this study, we developed an alternative: a game-based social training platform incorporating an eye-tracking system for children and preadolescents with ASD. The platform included three different modules of gaze-following, facial-emotion recognition, and complex social interaction skills for ASD participants to learn according to their age and cognitive functions. The modularized design of multiple games targeting specific cognitive skills of suitable age groups represents an essential step in rendering these platforms more accessible to ASD participants. To the best of our knowledge, the serious games with recording of eye-tracking signals proposed herein constitute a first-of-its-genre of computer games designed for ASD in East Asian countries. Our findings suggest that these atypical gaze patterns are reliable biomarkers for evaluating the social and cognitive functions of individuals with ASD when they play social interaction games. The results showed that children with ASD spent less time upon positive emotional expressions and multiple targets, compared to TD participants. The results of the social interaction module for the platform further demonstrated a decreased fixation time for social-related facial emotion expressions and prolonged saccade durations in participants with ASD. The eye-tracking results were comparable with previous studies of ASD, which demonstrates that eye-tracking signals are reliable biomarkers for evaluating the improvement of cognitive functioning and indicates the validity of the newly developed serious games. We hope that these findings will improve the quality of assessment and intervention procedures for children with ASD.

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