Enhance Affective Expression and Social Reciprocity for Children with Autism Spectrum Disorder: using Virtual Reality Headsets at Schools

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Social-emotional deficits in school-aged children diagnosed with autism spectrum disorder (ASD) greatly hinder these children from fully participating in various school activities in the inclusive education setting. Previous studies have demonstrated evidence regarding the effectiveness of using Virtual Reality (VR) for enhancing the children's affective expression and social reciprocity. However, considering the technical and logistical complexity of the enabling hardware and software systems, how such approaches can be effectively and sustainably delivered in the school setting remains underexplored. This paper presents a study that utilised VR headsets to enhance affective expression and reciprocity for children with ASD and explored how the approach could be effectively and sustainably delivered at schools. A total of eight VR learning scenarios were designed based on Kolb's experiential learning framework. 176 children aged 6-12 with a clinical diagnosis of ASD participated in the study. The statistical analyses showed that the participants who received the intervention significantly improved in affective expression and social reciprocity, compared to those who were in the control group. Moreover, the approaches to enhance long-term sustainability have also been presented and discussed in this paper.

Keywords: virtual reality; autism spectrum disorder; experiential learning; affective expression; social reciprocity

Introduction

Autism Spectrum Disorder (ASD) is a neurodevelopmental condition characterised by persistent deficits in social communication and social interaction across multiple contexts (American Psychiatric Association, 2013). Despite the growing trend of practising inclusive education, children with ASD experience a range of learning difficulties in mainstream schools due to their social-emotional deficits. For instance, children with ASD often have difficulties in interpreting body language and facial expressions as well as initiating and maintaining social interaction with their peers.

Thus, they regularly experience peer rejection and are seldom accepted by their typically developing peers (Rotheram-Fuller et al., 2010). Even worse, children with ASD are more likely to be victims of social exclusion and even bullying at schools (Symes & Humphrey, 2010; Cappadocia et al., 2012). Hence, more social-emotional training and support for them is urgently needed.

The effectiveness of technology-enabled interventions for ASD has been studied for decades. Advocated in Grynszpan et al. (2014)'s meta-analysis on technology-enabled interventions for ASD, the effectiveness of technology-enabled interventions is promising but further development and evaluation are needed. Among these technologies, VR is becoming more widely used in ASD interventions (Mesa-Gresa, et al., 2018). Previous studies have catered for the needs in the ASD population using VR, including daily-life skills (e.g., Lamash et al., 2017), social adaptation skills (e.g., Kandalaft et al., 2013; Ip et al., 2018), and vocational skills (e.g., Strickland et al., 2013; Smith et al., 2014). The core advantages of VR-enabled interventions, as mentioned in the abovementioned studies, are summarised as follow. First, it allows the educators to manipulate social scenarios according to the learning goals and students' needs. It can provide ASD children a safe and socially friendly environment for learning and practising. In real life, social situations can be complex and confusing to ASD children due to the great variety and number of stimuli in the environment. Having created realistic simulation of real-life scenarios, distracting stimuli can be minimized. The VR learning scenarios can even be programmed to support the manipulation of the speed or to merely "freeze" social interactions so that the students have more time to process what is happening in the scenarios (Vera et al., 2007), which could be useful to ASD students who often have difficulties perceiving social interactions. Visual tips can also be offered to them on the screen, which can further assist their perceiving of facial expressions and social interactions. Second, the visually captivating nature of VR environments could be appealing to children, potentially motivating them to engage in the training. Lastly, the VR learning scenarios can be programmed to simulate different kinds of real-life situations, so that students can practise and generalise skills in particular settings (Strickland et al., 1996; Parsons & Mitchell, 2002; Ip et al., 2018).

While the Cave Automatic Virtual Environment (CAVE) first developed by Cruz-Neira et al. (1993) can provide highly immersive experience, its limitations - immobility of the system, high maintenance cost, and the special requirements for the venues - could restrict the number of potential beneficiaries of such learning facility. More recent off-the-shelf VR headsets (a.k.a. Head-mounted Displays (HMDs)) like HTC VIVE, Oculus Rift, and Oculus Quest can hugely improve the accessibility and minimise the technical and logistical complexity. The use of HMD enhances the feasibility of delivering VR intervention for ASD children at schools, while providing a similar or even higher level of immersion. In early 1990s, Strickland et al. (1996) conducted a pilot study using the VR headset on a 7.5-year-old girl and a 9-year-old boy with ASD, which showed that both participants found the VR helmet (headset) acceptable, and they could identify familiar objects and their attributes, spotted and navigated towards the objects in the VR scenarios. The results were encouraging, given that the headset used in their study was bulky and low-resolution. Using off-the-shelf VR software and contents, Newbutt et al. (2016) conducted a pilot study on ASD individuals' acceptance of modern VR headsets. Their results corroborated the early findings regarding the high acceptance of the VR headsets by the participants. Li et al. (2018) further investigated the feasibility of using VR headsets for ASD intervention that required more complex social interactions through motion-tracked controllers in a custom-made VR scenario. The results from the case study showed that the participants on all three ASD severity levels (American Psychiatric Association, 2013) accepted the headsets and interacted with the virtual objects and agents proactively.

This paper presents a VR-enabled training programme developed to enhance the emotional and social skills of children with ASD studying in mainstream schools. The main contributions of this study are listed as follows. First, the design of the eight VR scenarios was based upon a solid and well-studied theoretical foundation - Kolb's experiential learning model (Kolb, 1984); this allowed us to examine the adoption of the theoretical foundation via empirical methods. Second, the scale of the study was significantly larger than that of the previous studies, which enabled us to collect more substantial evidence on the effectiveness of the VR-enabled training programme for the ASD population. Lastly, this study addressed some issues regarding the use of VR headsets in training children, such as the trainer's role as a facilitator during VR exposure and sustainability of the VR program.

Related Work

Applying virtual reality in education

Over the last few decades, VR has been adopted to provide an immersive and engaging learning environment in various education settings. Brooks (1999) first defined the technical capabilities what VR systems, as we know today, should have. There exist various types of VR systems for delivering highly interactive and authentic VR experiences in education (Kamińska et al., 2019). VR headsets (HMDs) are one of the most common types. Typically, each VR headset is equipped with two displays, separately projecting images into the user's eyes. External and/or internal sensors are used to track the translations and rotations of the user's head for computing the correct perspective of the rendered images. These enabling technologies can induce perceptual illusions such as presence (Steuer, 1992; Slater et al., 1994) and embodiment (Kilteni et al., 2012), which can hardly be induced in other technology-mediated environments.

Mikropoulos & Natsis (2011) first defined the educational use of VR by emphasizing the unique learning experience enabled by the technology, the pedagogical foundations for designing the learning experience, and the requirement of well-defined learning outcomes. This definition clearly distinguishes the educational use of VR from other purposes of use, such as for entertainment. Merchant et al. (2014) systematically reviewed articles reporting empirical studies that used VR for K-12 and higher education. The meta-analysis result showed the potential of using VR for education and presented its numerous advantages, but also called for future studies to "*test more design variables and interesting interaction effects of design features*" (p. 37). Luo et al. (2021) observed and reported in their more recent systematic review covering 157 empirical studies that more and more recent studies employed the pedagogical designs, which were dedicated to VR enabled learning. The authors also suggested that VR could be more suitable for teaching abstract concepts or procedural knowledge via authentic problem solving, as well as changing learners' affect and attitude.

VR has also been applied to training individuals with special education needs. Powers & Melissa (1994) discussed the potential and challenges of using VR and related technologies for educational purposes on people with special needs. Although technological obstacles like the cost-effectiveness of using the technologies, complexity of hardware and software, and system useability, have been largely resolved, there exist the challenges related to the nature of special education, especially the need for highly customised learning contents to cater to the wide spectrum of special needs, which was seldom addressed thoroughly in later studies. A few empirical studies first explored the use of VR among people with hearing impairments (Passig & Eden, 2000, 2001). The results showed that with a proper design of the learning content, the technology could enable enhancement in induction skills and spatial cognition for people with hearing impairment. Ip et al. (2013) explored the use of multi-sensory VR to enhance pre-learning skills of children with severe intellectual disability (SID). The empirical study demonstrated the feasibility of delivering VR-enabled learning in a special school. However, the authors did not report evaluations on the effectiveness. Based on spatial cognition models, Landuran & Sauzéon (2019) studied the use of VR for navigation aids among individuals with Down syndrome (DS). The empirical result demonstrated the advantages of VR in spatial cognition training among people with DS. As the nature of VR and related technologies could well meet the learning needs of the ASD population, there is a recent focus of using VR for ASD intervention, which will be reviewed and discussed in the later section.

Social-emotional impairment in children with ASD

ASD is characterized by persistent deficits in social-emotional reciprocity across multiple social contexts (American Psychiatric Association, 2013). Social impairment in young children diagnosed with ASD is associated with a lack of joint attention or joint engagement as well as reduced frequency and quality of peer interaction (Kasari & Patterson, 2012). Joint attention refers to the ability to coordinate attention with another individual on certain objects or events, with both individuals being aware of each other's attention (Mundy, 2003). It reflects early social interest and motivation, affects the ability to sustain social engagement, thus plays a significant role in the development of friendship (Freeman et al., 2015). Children with ASD have insufficient social interests, and even when they do show social interests, they lack the social skills to make appropriate interactions with others (Bauminger et al., 2003; Deckers et al., 2014). Thus, it is necessary to train social skills and teach them social norms, as well as providing them the opportunity to practice social interactions.

Besides, individuals with ASD are less capable of understanding others' emotions (Tavassoli et al., 2018; Wallace et al., 2008). Many of them fail to use adaptive strategies for emotional regulation (Bruggink et al., 2016, Sofronoff, et al., 2007). Recent literatures suggest that emotional dysregulation is associated with social (Reyes et al., 2020; Goldsmith et al., 2018) and behavioural deficits (Berkovits et al., 2017), and is related to other core ASD symptoms such as restricted/repetitive behaviours and sensory abnormalities (Samson et al., 2014). Poor emotional regulation could greatly hinder the development of social relationships and even lead to depression (Pouw et al., 2013). Some of the children with ASD are easily irritated by sensory overload and exhibit dysregulated reactions. This situation further worsens their social participation (Tavassoli et al., 2018). In summary, these deficits greatly hinder the children from developing peer relationships and functioning well in the daily classroom environments.

Virtual reality enabled training for the ASD population

VR is widely considered as a promising tool for mediating ASD interventions. From the human experience perspective, the uniqueness of VR is the provision of highly interactive and authentic environment, which can deliver *the sense of presence* to its users (Steuer, 1992; Slater et al., 1994). The virtual scenarios can be designed to simulate an infinite number of settings with high fidelity, supporting the design of different theory-driven interventions. Studies have been conducted to target at the deficits in ASD children using VR technology. Grynszpan et al. (2014) conducted a systematic review of studies with pre-post design to evaluate technology-based interventions for children with ASD. The overall mean effect size for the posttests of the included studies approached medium range ($d = 0.47$), showing the effectiveness of the training, hence supporting *"the continuing development, evaluation, and clinical usage of technology-based intervention for individuals with autism spectrum disorder"* (p. 346). For vocational skills, Strickland et al. (2013) investigated the efficacy of using web-based VR for teaching job interview skills to 22 teenagers with HFA in a virtual office space. This randomised controlled trial (RCT) study showed that participants who received the intervention exhibited significant improvement in their job interview skills. Smith et al. (2014) also studied the effectiveness of using VR for vocational training on a sample of ASD using a virtual agent who was capable in simple social conversation via the speech recognition software. By doing so, the trainers no longer directly interacted with the trainees but only needed to facilitate the interactions between the trainees and the virtual agent. This single-blinded RCT study involving 26 individuals between the ages of 18 to 31 with ASD showed significant improvements in job interview skills and self-confidence of the trainees. Besides, Lamash et al. (2017) used VR to train daily life skills, such as buying groceries in the supermarket.

Studies have suggested that VR-enabled experience enabled ASD children to learn and understand social skills and apply them to real-life settings (Strickland, 1997; Bellani et al., 2011; Parsons & Cobb, 2011; Parsons, 2016). Rajendran (2013) thoroughly examined the application of most important psychological theories, e.g., theory of mind, joint attention, and self-monitoring, which could be applied to guide the design of the VR learning scenarios. The author also suggested that the area of research could offer a chance for *"better inclusivity for individuals with autism within a digital society"* (p. 334). Didehbani et al. (2016) designed a series of VR scenarios for training social cognition among 30 children with High-Functioning Autism (HFA) aged between 7 and 16. They successfully enhanced the participants' emotion recognition, social attribution, and executive function. Ip et al. (2018) used a CAVE to deliver six learning scenarios specifically designed to improve the affective expression and social adaptation skills in school-aged children with ASD. The RCT study showed that children who received the 28-session training significantly improved on affective expression and social adaptation skills compared to the control group. However, the authors also mentioned that the CAVE and related enabling technologies were "expensive to be widely implemented across a larger area to better serve the population" and called for further examination of other VR environments or systems, such as VR headsets. Lee (2020) applied Kinect Skeletal Tracking System and augmented reality to enable trainers to control virtual characters' body movements and facial expressions in real-time to interact with ASD children, and the results suggest that their social interaction skills improved. However, as mentioned by the author as a limitation, the use of innovative technology limited the number of beneficiaries since few schools had installed the required equipment for running the program. Research with greater size and more widely applicable designs would be needed. Among the different types of VR equipment, HMDs are more affordable than CAVE, able to prevent ASD children from being disturbed by external stimuli and enhance presence. Studies have demonstrated the acceptance, safety, and usability of VR headsets on children with ASD (Strickland et al., 1996; Newbutt et al., 2016; Malihi et al., 2020). This study aimed to design a training program which utilises the highly portable HMDs to enhance the applicability in more schools.

For the training design, Kolb's experiential learning theory (Kolb, 1984) was applied to facilitate learning. The rationale was illustrated in a previously published paper (Authors, 2019) and detailed in the Method section of this paper. One key challenge of implementing experiential learning was spotting the timing and approaches in terms of providing assistance and facilitation to the children for reflection of new experience, given the limitation of using VR headsets: unlike CAVE-like VR systems, when using the VR headsets, the children could not see their trainers. As a result, trainers found it difficult to identify when and how to offer help and facilitate children's learning. To mitigate the complication, programme-controlled virtual agents with pre-scripted dialogues inspired by Pan et al. (2012) were placed at the locations where the children might need facilitation. The virtual agents always appeared in the virtual scenes as humanoid agents whose identities fit the plot of the setting (e.g., a schoolteacher). During the training, the trainers' role had been shifted to keeping the children safe during the intervention and providing psychoeducational counselling in critical situations, for example, when the children were in emotional outbursts.

Research Questions

Based on the previous studies and existing gaps in the research area, this study aims to answer one key research question - can the VR-enabled training program, which takes place in the school setting, enhance affective expression and social reciprocity of children with ASD? This question regarding the effectiveness shall be answered by comparing the quantitative data collected from the training group to that from the control group. Moreover, unlike previous research studies in which the interventions were mainly delivered in laboratory settings, the psychoeducational interventions of this study were delivered entirely at the participating schools, involving both the trainers from the research team and the schoolteachers. Hence, feedback and comments from schoolteachers were also collected to provide more insights qualitatively.

Method

Participants

Chinese-speaking primary school students (aged 6 to 12 years) with a clinical diagnosis of ASD were recruited through contacting mainstream primary schools in [country/region is hidden to keep the manuscript anonymous] by a territory-wide random sampling. Since all the students had been admitted to mainstream primary schools, none of the students was on the low-functioning end of the autism spectrum or had cognitive disabilities. During the experiment, the grades of the students ranged from primary one to primary six. Briefing sessions were held for parents who expressed interests in having their children participate in this study. A total of 196 students from 16 schools joined the study. Since the VR-enabled sessions were scheduled in the afternoons of school days during which students might also have other after-school activities to participate in, 20 of the 196 invited students dropped out, of which 17 students could not join the study due to time constraints. After randomisation at the school level, 98 participants were assigned to the intervention group and the other 78 participants were assigned to the control group. During the study, there were three dropouts from the intervention group and three dropouts from the control group due to personal reasons, such as time constraints and illness; all other 95 participants in the intervention group completed the VR-enabled training sessions. However, 47 participants from the intervention group and 16 participants from the control group did not complete the post-assessment due to the school closure during the Coronavirus disease (COVID-19) outbreak and the strict social distancing rules imposed which prevented us from conducting the post-assessment. Eventually, by the end of the study, the valid number of participants to be included here was reduced to 107, with 48 participants from the intervention group and 59 participants from the control group. The gender distribution (88 males and 19 females) among the 107 included participants roughly matches the prevalence data in [country/region is hidden to keep the manuscript anonymous] (Authors, 2008) and the United States (Baio et al., 2018). The study recruitment process is shown in Figure 1.

Experimental design

This study adopted the quasi-experimental design (Campbell & Cook, 1979) and the wait list control design. Due to the heavy involvement of the schools, it was not feasible to randomise the experiment on the individual participant level. The schools had tight schedules of after-school activities and hence were not able to arrange teachers to assist across different training periods. Also, the repeated measures approach was adopted. Within two weeks before the intervention started, all participants joined the pre-assessment. After they completed the training program, they were assessed with the same set of measures again. The research was approved by [the name of the ethics committee is hidden to keep the manuscript anonymous].

Hardware and software environments

The VR headsets used in this study were Oculus Rift with the Touch controllers. The controllers support intuitive interactions in the virtual scenes, such as pointing using index finger and grabbing. Both the headsets and the controllers support 6-degree-of-freedom (6-DoF) tracking; the translations and the rotations of the user’s head and two hands in three-dimensional space can both be tracked with sub-millimetre accuracy in real-time. The tracking was achieved through the two sensors that come with the headset. The sensors were placed on top of the desk together with the Lenovo Legion Y520 laptop computer, which the headset was also tethered to. The laptop computer was equipped with a single NVIDIA GeForce GTX 1060 mobile graphics card, 16GB of main memory, and 256GB of a solid-state drive. With some optimisations to the contents, the VR headset was able to maintain its maximum 90Hz refresh rate during the whole exposure.

The intervention normally took place in the multi-purpose rooms for extra-curricular activities in the participating schools. Each setup occupied a 2.5-meter-by-2.5-meter space (see Figure 2), providing children enough space to interact with the virtual objects and agents inside VR.

The virtual scenes and agents with their corresponding animations were created in Blender (https://www.blender.org/). To minimise the cost of creating new three-dimensional arts, a great portion of materials were adapted from the authors' previous work (Author, 2018). All the necessary materials, including the voice recordings and sound effects, were imported into Unity (https://unity.com/). Optimisation methods, such as the use of baked lightmaps and reflection maps, were set and handled by Unity. The flow logic and the interaction logic were programmed using C# programming language. The finished VR scenarios were compiled to become executable with Oculus (https://www.oculus.com/) software installed.

Virtual reality learning scenario design

The overall design objective of the VR scenarios was to create a series of authentic virtual scenes that simulate the typical school environment, in which the children were able to develop and practice their emotional and social skills following Kolb's experiential learning model (Kolb, 1984). Kolb (1984) suggested that *"learning is the process whereby knowledge is created through the transformation of experience"* (p. 38). VR enables ASD children to experience the social scenarios in a rather controllable environment compared to quick-changing social events in real life. Each scenario has more than one session for children, thus giving them more time and opportunities to comprehend, digest and experiment skills and knowledge, i.e., create and recreate knowledge throughout the training. The variations also allowed them to practise and generalise learnt skills when conflicts occur. More complex and challenging scenarios were repeated up to five times with slight variations. In the debriefing part, trainers would facilitate a discussion on what they have been through and how they attempted to apply the learnt skills.

To illustrate the step-by-step process, Kolb's experiential learning model (1984) includes four stages: concrete experience, reflective observation of the new experience, abstract conceptualization, and active experimentation. Specifically, to enable the concrete experience stage, the current training program was designed to elicit experiential learning by creating various social contexts and situations in daily life environments, in which the children were first experienced what it is like to be in certain social interactions, gained the knowledge and skills such as social norms (e.g., greeting people, keeping quiet in the library) and interaction skills (e.g., conflict resolution). The participating schoolteachers were invited to collaborate with our team of educational psychologists to co-design these social contexts and situations in the school environment. Next, to enable the reflective observation stage, children were encouraged to reflect upon their experiences by trainers or visual hints in the VR learning scenarios. Based on our previous experience and prior studies, this stage could be challenging for children with ASD, especially when considering the VR headset could greatly hinder facilitation. Thus, to make the reflective observation stage more effective, virtual agents with pre-scripted dialogues were employed in the VR learning scenarios. This approach borrowed the idea from Pan et al. (2012) that used a female agent with attention and interpersonal distance awareness for testing social anxiousness as well as confidence in men during social interaction. Our approach here aimed to allow various types of interpersonal social interactions to happen in the VR learning scenarios, including the provision of facilitation and guidance, so that the experiential learning model could be applied without the need for much facilitation and guidance from the trainers and/or schoolteachers. Thirdly, the enabling of abstract conceptualization was designed around the understanding and conceptualising emotions in social contexts, which are closely related to quality social interactions (Lopes et al., 2005; Van Kleef, 2010). Hence, interventional activities on facial expression recognition and identifying oneself emotions were embedded in relevant, meaningful contexts in the VR learning scenarios to facilitate the abstract conceptualization stage of the experimental learning. Specifically, previous studies suggested that individuals with ASD often had difficulties in recognising facial expressions of fear, sadness, and disgust (Wallace et al., 2008) and these individuals highly relied on different facial features to recognize facial expressions (Wallace et al., 2008; Harmset al., 2010; Bekele et al., 2013). Here, an art class scenario (learning scenario 3.2, see Table 1) that required the learners to complete several tasks related to facial expression was included. More specifically, the participants were asked to match jigsaw pieces of facial features (e.g., eyes, eyebrows, mouth, etc.) under the guidance of a virtual agent - the art class teacher. Six basic emotions were included (Ekman, 1999). By doing so, the participants were expected to pay more attention to different areas of faces when recognizing expressions. A previous study suggested that reducing the pace of presentation of facial expressions could further enhance facial expression recognition in the ASD population (Tardif et al., 2007). Hence, static emoji-like hints were added next to the virtual agents that were interacting with the participants to facilitate the recognition of the avatars' reactions, further contributing to better reciprocal social interactions in the scenarios. Moreover, the participants were asked to identify their own emotional states in the VR learning scenarios when entering the abstract conceptualization stage. For example, when social situations or conflicts were programmed to happen in the scenarios, such as a virtual classmate teasing the child participants in learning module 4 (see Table 1), they were prompted to identify their emotional states. The participants were expected to better understand and conceptualise emotions through such activities and visual prompts. Lastly, to enable active experimentation, the participants were encouraged to apply the newly gained repertoire of skills and knowledge to resolve the situation and progress to the next activity in the VR learning scenario. The positive reinforcement design philosophy was applied here, and the reinforcement was presented in an appealing way with gamification elements in the VR learning scenarios. The child participants in this study were highly motivated to engage in the social interactions in the scenarios. They were given positive reinforcements, such as seeing a few colourful stars after each task was completed, being praised by the virtual agents, trainers, and schoolteachers for active participation, getting virtual and physical stickers at the end of each session, etc. Moreover, the VR learning scenarios were designed to let the children practise social interactions without real negative consequences. This design further encouraged the participants to reflect upon new strategies for tackling the challenges, which is crucial to the experiential learning process. These new strategies involving reciprocal social behaviours can be easily transferred to real-life situations, because the entire set of scenarios, designed based on the children's real life, provided authentic contexts for promoting reciprocal social behaviours, which involve the recognition of social cues (e.g., facial expressions, body gestures, etc.) of others in the given contexts, appropriate interpretation of those cues, appropriate behavioural responses (Constantino et al., 2000; White & Scahill, 2007). Through applying skills to new scenarios and real life, they could gain more concrete experience and the whole process could form a loop in the VR learning scenarios as well as a larger loop covering social situations in both VR and real life.

Based on the above-mentioned approach of applying the experiential learning model, eight VR learning scenarios were designed and developed under five different learning modules (see Table 1), following five different learning objectives for children aged 6 to 12 in the inclusive education setting. Some screenshots of the scenarios were included in Figure 3. To facilitate the sequential progress of the learning, a task list was included in all scenarios. The children could press a designated button on one of the two controllers to toggle the display of the task list and check the next task they were supposed to work on.

Module 1 was an introductory scenario designed to teach children how to navigate in the VR learning scenarios and interact with virtual avatars and objects. The navigation and interaction techniques, including greeting the virtual agents, picking up virtual objects, and having dialogues with the virtual agents, could be applied to all the other seven scenarios. To have dialogues with the virtual agents in the VR learning scenarios, the child participants needed to choose one pre-scripted dialogue option, which was shown as a speech bubble with texts and animations in the scenarios, by speaking and touching the bubble (see Figure 3). We chose to implement the interactions in this way because free-dialogue-based interactions might deviate too much from the designated social situations and/or outcomes, which could be very costly to implement and might not achieve the intended learning outcomes. The use of task lists was also introduced in this module. The task list was designed to provide clear objectives and help those children with deficits in executive functioning. Upon the completion of the tasks, the children would receive a virtual chop on the task list and sparkling, which served as positive feedback.

Learning module 2 focused on executive functioning and daily life skills. It consisted of two VR learning scenarios: one was preparing to go to school at home (scenario 2.1), and the other was to travel to school and submit homework in a typical classroom in a primary school (scenario 2.2). The children were expected to learn how to greet others, prepare themselves for a school day, and follow the instructions given by their caretakers and schoolteachers. In these two VR learning scenarios, the children would also face the variations. The variations might randomly appear to further challenge the children as the scenarios were used repeatedly. For example, in scenario 2.1, children were required to enter the bathroom for daily routines. In the second and third sessions, they would find that someone was using the bathroom when they knocked on the door. They might also find that the lift was fully occupied when they wanted to go to the ground floor to take the school bus. In scenario 2.2, the school bus might be in a traffic jam thus the journey would take longer than usual. Also, after alighting from the school bus while waiting at the crosswalk, there might be a person who crossed the road while the pedestrian lights were still red.

Learning module 3 focused mainly on emotional skills and consisted of two VR learning scenarios. The first scenario (scenario 3.1) was about learning the social norms in the school library, which was designed to help the children understand the importance of following social norms and practise emotion regulation. The variation that the children would face was some peer students talked loudly in the school library and one student jumped the queue while the children were waiting at the circulation counter. In both variations, the virtual students broke the social norms and the children needed to learn how to deal with these situations in socially appropriate ways. The second scenario of this module (scenario 3.2) targeted at emotion recognition and expression. This was achieved through attending a virtual art class, during which the children were required to complete three minigame tasks regarding emotion recognition and understanding what other people would feel in certain situations. There were no variations in scenario 3.2, but the minigame tasks were randomly picked from a large set of tasks.

Learning module 4 was designed for learning and practising social skills. It comprised two VR learning scenarios: one was having social interaction during recess (scenario 4.1) and the other was forming a group with classmates and responding to social stories in a physical education class (scenario 4.2). The social interaction in scenario 4.1 comprised conversations with two virtual classmates discussing things that happened around them so that children could practise social reciprocity. Each of the five sessions had a different topic for children to practise. During the conversations, children were expected to choose the socially appropriate dialogue options in response to what the virtual classmates just said. For example, a virtual classmate lost his wallet, and the child participant should choose a dialogue option that could comfort him instead of teasing him. The children were also exposed to social conflicts in these scenarios. For example, in scenario 4.1, a virtual student might jump the queue while the child participants were waiting at the tuck shop. In scenario 4.2, the participants might be refused from joining a group. They needed to respond calmly and communicate with other virtual schoolmates by selecting one of the socially appropriate dialogue options (e.g., "Please go to the end of the queue", "It's fine") to resolve the conflicts. There were also variations in these two scenarios. In scenario 4.1, the food chosen by the children might be sold out and the group they chose to join might be full already in scenario 4.2.

Learning module 5 was the consolidation module. The VR learning scenario was designed based on a funfair on the school playground. In this module, the children needed to finish three tasks in three separate game booths regarding skills they learned in previous modules. After they finished, they could redeem a virtual present. The children also needed to handle social conflicts, e.g., a virtual classmate jumping the queue when other students were queuing up for a game booth. The design of this module aimed to provide a new social context for children to consolidate and generalise the knowledge and skills the children had gained through previous learning modules.

Measures

The 60-item Raven's Progressive Matrices (RPM) (Raven & Court, 1998) test was administrated as part of the pre-assessment for estimating the participants' non-verbal IQ. The scoring was based on the norm obtained in the [country/region is hidden to keep the manuscript anonymous] sample. Reliability of the test was.91 (Cronbach's alpha) in a sample of 300 [country/region is hidden to keep the manuscript anonymous] children aged 6-11 years (Authors, 2020). Two subtests, Affective Expression and Social Reciprocity, of the [country/region is hidden to keep the manuscript anonymous] version of the Psychoeducational Profile Third Edition (PEP-3) was administered to assess the skills and behaviours of the children with ASD (Schopler, Lansing, Reichler, & Marcus, 2004; Shek, Tsang, Lam, Tang, & Cheung, 2005; Shek & Yu, 2014). Lower scores indicate more severe impairment.

Procedure and protocols

Before the assessment and training were commenced, parents attended a briefing session that aimed to introduce the research ethics (e.g., the participants' rights) and the procedure of the study (e.g., the VR exposure time and the number of planned sessions). The research team obtained a written consent and a report of formal diagnosis of ASD from each of the parents. Briefing sessions for the participating schools were also organized in advance, during which the research team obtained the written consent from the school representatives.

The training spanned 15 weeks. In each week, two training sessions were conducted in the schools, making a total of 30 VR-enabled training sessions. All the participants from the training group were asked to join the pre-assessment within two weeks ahead of the first training session and to join the post-assessment within two weeks after the last training session. The control group took part in the pre-assessment and post-assessment during the waiting period where they did not participate in the training sessions. They received training after the post-assessment was completed.

Each of the 30 VR-enabled training sessions consisted of three parts: briefing, VR exposure, and debriefing. A maximum of four children from the same school with similar ages were assigned to the same session. During the briefing, the trainers prepared the children to get ready for the VR exposure stage. The basic principle was to keep the children cognitively engaged in the training and emotionally stable. The trainers from the research team, schoolteachers and teaching assistants observed each student's condition in the briefing stage. Before proceeding to the VR exposure stage, the children were also told that if they felt any discomfort, they had to notify the trainers and the training would be terminated. During the VR exposure stage, the children took turns to receive the VR-enable intervention. One trainer from the research team, or one schoolteacher who had finished the 7.5-hour training provided by the research team, facilitated the VR exposure and took care of the children's safety during the exposure. Another trainer or schoolteacher, who had yet to finish the teacher training, would observe. The assistant, who served a supportive role, guided the rest of the group to attend to the computer screen for observing what was happening in the VR learning scenarios. In the debriefing stage, the participants were instructed to express their thoughts and feelings concerning their experience in the VR learning scenarios so that the trainers could advise on the application of the learnt knowledge in real-life situations. The trainers also rewarded the children with stickers as a form of encouragement. The children were asked again if they had experienced any discomfort during the VR exposure. The trainers would assess and record the condition if any discomfort were reported by the children. The VR exposure stage usually lasted for 30 minutes (7 to 8 minutes for each child of the group), and the briefing and debriefing stage lasted for 15 minutes each, making the whole session last for around 60 minutes.

Data entry and analysis

To reduce the observer's bias, the raw scores were recorded, scored, and input to the computer by two research team members. The data analyses were performed using IBM SPSS Statistics (Version 26). Descriptive statistics were calculated and reported for each group at two time points. Chi-squared test was used to compare the proportion of male across the two groups. Paired sample t-tests were used to compare the change in affective expression or social reciprocity at pre- and post-assessments. One-way ANCOVA was used to determine if there was a difference in PEP-3 affective expression and social reciprocity subscale scores after the training across two groups (i.e., two conditions), while controlling for the participants' non-verbal IQ and pre-assessment scores. Mixed repeated measures ANCOVA was used to determine if there was a difference in PEP-3 affective expression and social reciprocity subscale scores before and after the training (i.e., two time points) across two groups (i.e., two conditions), while controlling for the participants' non-verbal IQ. A significance level of 0.05 was used across all analyses.

Results

Demographics

Of the 48 participants from the training group, 41 were male (85.4%); 47 of the 59 participants from the control group were male (79.7%). Chi-square test showed no significant difference in terms of the gender proportion between the two groups, $\chi 2$ (1, N = 107) = 0.60, p = 0.438. The mean age of the training group recorded in the first training session (M = 101, SD = 19.9) was significantly lower than that of the control group (M = 112, SD = 19.5), t(105) = -2.94, p = .004. This might be due to the nature of the quasi-experiment design. However, since biological age is not associated with ASD severity (Gotham, Pickles & Lord, 2012; Thompson, 2018), it cannot fully reflect the developmental level of children with ASD. Thus, age was not included as a covariate. Instead, childhood intelligence has been recognized as a strong predictor of developmental outcomes in ASD individuals (Magiati, Tay & Howlin, 2014) so it was used as a covariate in the following analysis. The non-verbal IQ of the training group (M = 93, SD = 15.6) did not significant differ from the control group (M = 92.5, SD = 16.5), t(105) = .153, p = .879. The demographics of the participants are shown in Table 2.

Affective expression

Firstly, paired sample t-tests showed that PEP-3 affective expression subscale mean score of the participants from the training group in pre-assessment (M = 16.1, SD = 5.16) increased after joining the training sessions (M = 18.7, SD = 3.67), t(47) = 4.28, p < .001, 95% CI [1.36, 3.77]; affective expression of control group in the pre-assessment (M = 18.7, SD = 3.29) was not significantly different from post-assessment (M = 18.0, SD = 3.97), t(58) = 1.22, p = .226, 95% CI [-1.88, .45]. The descriptive statistics are shown in Table 3. Next, a one-way ANCOVA was conducted to test the effect of group (training vs control) on affective expression post-assessment score, with non-verbal IQ and pre-assessment scores as covariates. The main effect of group was significant, $F(1, 103) = 5.08$, $p = .026$, partial $\eta2 = .047$ (see Table 4). That is, training group has a significantly higher score in affective expression compared to that of the control group after controlling for the non-verbal IQ and the pre-assessment score. The covariate, non-verbal IQ, has a marginally significant association with the affective expression score in post-assessment, $F(1, 103) = 3.02$, $p = .085$; another covariate, the pre-assessment affective expression score, was significantly related to the post-assessment affective expression score, $F(1, 103) = 17.9$, $p < .001$. Also, a mixed repeated-measures ANCOVA was conducted, with group (training vs control) as the between-subject factor and time as the within-subject factor, and non-verbal IQ as the covariate. There was a significant interaction effect between group and time on affective expression after controlling for non-verbal IQ, $F(1, 104) = 15.0$, $p < .001$, partial $\eta2 = .126$ (see Table 6).

Social reciprocity

Social reciprocity scores were also subjected to the three statistical tests. A paired-sampled t-test revealed that PEP-3 social reciprocity subscale mean score of training group was significantly higher in post-assessment ($M = 20.4$, $SD = 3.64$) than in pre-assessment ($M = 18.6$, $SD = 4.76$), $t(47) = 3.38$, $p = .001$, 95% CI [.74, 2.91]. For the control group, PEP-3 social reciprocity subscale mean score in post-assessment ($M = 19.7$, $SD = 4.70$) was lower than that in pre-assessment ($M = 20.7$, $SD = 3.18$), $t(58) = 1.66$, $p = .103$, 95% CI [-.19, 2.06]. The descriptive statistics are shown in Table 3. One-way ANCOVA was conducted to test the main effect of group on social reciprocity, with non-verbal IQ and pre-assessment scores as covariates. The main effect of group was significant after controlling for non-verbal IQ and pre-assessment score, $F(1, 103) = 5.43$, $p = .022$, partial $\eta 2 = .05$ (see Table 5). The results showed that the covariate, non-verbal IQ, was not significantly related to social reciprocity score, $F(1, 103) = 2.13$, $p = .147$; But another covariate, social reciprocity score in pre-assessment, was significantly related to that in post-assessment, $F(1, 103) = 30.6$, $p < .001$; Thus, training group showed significantly better social reciprocity than control group after the training. A mixed repeated-measures ANCOVA revealed that there was a significant interaction between group and time on the social reciprocity scores after controlling for non-verbal IQ, $F(1, 104) = 12.0$, $p = .001$, partial $\eta 2 = .104$ (see Table 7).

Discussion

Effectiveness of the VR training programme

The present study sought to examine whether the current VR-enabled training programme specially designed for children with ASD studying in mainstream schools could enhance their affective expression and social reciprocity (RQ1). Significant improvements in both areas were found in the children who received the intervention. The inter-group comparison showed a significant difference in the post-assessment affective expression and social reciprocity scores across the two groups, after controlling for the participants' pre-assessment scores and non-verbal IQ. Results from mixed repeated measures ANCOVAs with the non-verbal IQ as the covariate revealed similar insights, suggesting that there were significant interactions between condition and time on the participants' affective expression as well as social reciprocity. Also, this study has a large sample size compared to previous similar studies, even though the sample size of data for pre-post comparison has inevitably shrunk due to the pandemic. Among the 176 participants registered with us, 47 participants from the intervention group had to be excluded from the statistical analysis due to incomplete training or incomplete post-assessment. Likewise, 16 participants from the control group had to be excluded due to the incompletion of the post-assessment. Still, the resulting sample size involved 48 students in intervention group and 59 in control group from 16 schools in [country/region is hidden to keep the manuscript anonymous]. The results echo previous studies on affective and social skill training (e.g., Didehbani et al., 2016; Lorenzo et al., 2016; Ip et al., 2018), demonstrating the effectiveness of adopting VR in ASD interventions. However, unlike previous studies, this study, as far as we know, is the first large scale empirical study that investigated the delivery of affective-social skills training using VR headsets at schools. The encouraging results and the mentioned advantages of HMDs can greatly contribute to VR-enabled training in the inclusive education setting.

Reflections on the content design

The VR training program used for this study was designed using Kolb's experiential learning model utilising the specific strengths of using the enabling technologies. Four VR learning scenario design features, which were made to maximise the benefits of adopting VR, are highlighted and discussed here. These design features could provide important implications to the future practice of using VR for ASD training.

First, the employment of virtual agents with pre-scripted dialogue addressed the issue of providing facilitation or guidance while wearing the HMD. This approach borrowed the idea from Pan et al. (2012) and aimed to enable experiential learning, especially the abstract conceptualization and active experimentation stage without the need for much facilitation and guidance from the trainers and/or schoolteachers.

Second, intervention activities related to affective expression were delivered in social contexts in the VR learning scenarios, which were plotted based upon real life situations. Our observations and the schoolteachers' feedback suggested that the approach could indeed enhance the generalisation from VR to real life, which was also suggested in prior studies (Parsons & Mitchell, 2002; Ip et al., 2018). The variations we added to the scenarios, which appeared randomly, also abounded in the plotting when the scenarios were used in multiple sessions.

Thirdly, the participants were encouraged to identify their own emotional states in the VR learning scenarios. When social situations or conflicts were programmed to happen in the scenarios, the child participants were immediately prompted to identify their emotional status. This allowed the participants to receive adequate practices of affective expression as well as regulation in a reciprocal and reflective manner across different social contexts.

Finally, positive reinforcements were presented in an appealing way with gamification elements in the VR learning scenarios as well as in real life. The child participants in this study were highly motivated to engage in the social interactions in the scenarios. They were given positive reinforcements, such as seeing a few colourful stars after each task was completed, being praised by the virtual agents, trainers, and schoolteachers for active participation, getting virtual and physical stickers at the end of each session, etc. Moreover, the VR learning scenarios were designed to let children practise social interactions without real negative consequences. This design further encouraged the participants to reflectively think about new strategies for tackling the challenges, which is crucial to the experiential learning process.

Cooperation with schoolteachers

Teacher-trainer communication is also critical to achieving the intended learning outcomes. During the study, the participating schoolteachers and professional staffs actively communicated with the research team, making it easier for the research team to monitor the progress of the children achieved in the actual school settings and to identify the potential improvements that could be done to both the VR learning scenario designs and the overall design of the training programme. For example, some schoolteachers and professional staffs reported that in learning module 4, many of the children found it challenging to deal with the simulated social conflict during which the children faced verbal bullying. The design of the VR learning scenario aimed to help the children better perceive and respond to bullying, which is an alarming issue nowadays at schools (Van Roekel, Scholte, & Didden, 2010; Humphrey & Symes, 2010; Chen & Schwartz, 2012). The research team quickly identified the actual challenges faced by the children during the training and recommended the schoolteachers and professional staffs to provide specific guidance during the briefing stage. Because most of the participants were not able to appropriately respond to verbal bullying in the school settings, extra measures were needed to prevent bullying towards students with special education needs. This can be achieved by developing additional VR learning scenarios in future studies.

Schoolteacher feedback and comments

Feedback from the participating schoolteachers was encouraging. In total, 17 participating teachers provided their feedback on the VR-enabled programme in written form. Their feedback could be consolidated and summarised in the following aspects. First, the use of immersive and interactive VR scenarios simulating real life scenes and situations for affective expression and social reciprocity training was welcomed and perceived as useful by the schoolteachers. Teacher C wrote that the VR learning scenarios were “very practical [and] provided real life scenarios and situations” for the child participants. Teacher N wrote that “all the [VR learning] scenarios are [designed based on] the situations that students may face in their daily life.” Besides, the schoolteachers used words, such as “useful” and “helpful”, to express their observations regarding the training outcomes. Teacher K also wrote that "the [participating] students' signs of progress have been observed" in the school setting. The transfer and generalisation of knowledge and skills learned in VR are the key to the success of using VR for ASD training but heavily underexplored, as pointed out in several studies (Parsons & Cobb, 2011; Mesa-Gresa et al., 2018; Bozgeyikli et al., 2017). Although we did not measure the transfer of skills to real life, positive feedback regarding the change of students' behaviours in the school setting is encouraging. Second, the use of tasks involving emotion recognition in simulated social contexts to enable the abstract conceptualization stage of the experiential learning model was believed to be one of the best designs of this programme by the schoolteachers. When being asked about the best part of the programme design, six of the 17 schoolteachers who provided their feedback mentioned affective expression and/or emotion recognition. Considering the importance of emotion recognition in social communications and the observed worse performance in emotion recognition among ASD individuals (Rump et al., 2009; Uljarevic & Hamilton, 2013; Shanok et al., 2019), the programme was designed deliberately to help students with ASD in this area. Additionally, inspired by previous studies, our design benefited from the advantage of VR, that allows the practice of emotion recognition in given social contexts; such interactive and context-based approaches could be more effective than conventional ways of training using static images or short video clips (Baron-Cohen et al., 2009; Lorenzo et al., 2016; Farashi et al., 2022). However, some research questions still need to be further investigated. Lastly, the schoolteachers liked the design choice of having a finite number of interaction options, because open-ended dialogues could not help to plot the scenarios as well as to reach the intended training outcomes. They also liked the idea of asking the child participants to speak out before making the choices. Teacher M wrote that the design and the training "provided opportunities for the [participating] students to make choices and speak out” in the contexts and situations that “were very similar to real life.” Both Teacher F and G mentioned that interactive storytelling which required children to choose proper responses had “a certain variety from session to session” and made the training “engaging to the [participating] students.”

In general, the feedback and comments from the participating schoolteachers supported the use of VR for ASD training in the school setting and aligned with the quantitative results. Additionally, they lead to important and interesting research questions that may be out of the scope of this study but worth investigating in future research.

Acceptance and sustainability

One concern would be the children’s acceptance of VR headsets. Also, most of the headset manufacturers do not recommend using VR headsets on children under the age of 13. To ensure children’s safety, the authors have consulted research articles regarding the effects of using VR headsets on children before the study was carried out. Previous studies have raised the concern that VR exposure may damage the immature visual system (Peli, 1990; Rushton & Riddell, 1999). However, no reliable data has been reported to support this risk. While studies on the feasibility of using off-the-shelf VR headsets on children with ASD reported minimal negative effects of exposure (Newbutt et al., 2016; Li et al., 2018), all members of the research team proceeded with caution and all trainers and schoolteachers were required to pay close attention to participants to check if there was any discomfort during the exposure. By the end of the study, no negative effects of exposure beyond eyestrain or fatigue were observed or reported, which generally matches the findings reported by Tychsen & Foeller (2020) in their quantitative research.

The sustainability of such VR-enabled training cannot solely rely on the accessibility of the VR hardware. By the end of the study, training workshops were provided to 57 schoolteachers and professional staffs from 16 participating schools, making the first step in expanding the number of beneficiaries. These schoolteachers and professional staffs were trained to deliver the VR-enabled training to the children independently (without the trainers' assistance provided by the research team). Upon the completion of the study, all 16 participating schools were granted the whole set of hardware installed with the VR software used in the training program. Two of the schools even purchased additional sets of hardware to continue delivering the psychoeducational intervention to new students with ASD by the trained schoolteachers and professional staffs.

Limitations

A major limitation of the current study is the employment of quasi-experiment design. As explained in the method section, it was not feasible to employ the RCT experiment design for this study, due to some constraints imposed by the schools. The team was not able to randomize the current sample at the individual but school level. The participants from the control group exhibited higher baseline scores on both the PEP-3 affective expression subscale and social reciprocity subscale in the pre-assessment (see Table 3). Hence, the pre-assessment scores, which showed significant associations with the post-assessment scores, were controlled as a covariate in the data analysis. Also, the control group did not receive any training using non-VR approaches. The research team was not able to compare VR training with non-VR approaches with similar teaching content. It was the use of VR attracted the schools to participate in the study, hence the difficulty in recruiting participants to join non-VR training sessions. A waitlist control design was adopted to provide all students the opportunities to participate in the VR training.

The second issue is the unavailability of follow-up data for examining the retention effect of the intervention. Due to the COVID-19 pandemic, schools in [country/region is hidden to keep the manuscript anonymous] were required to close from time to time. The research team was unable to test the participants again three months after the post-assessment and evaluated the retention of the improvements. However, the schoolteachers welcomed the approach. As the pandemic situation in [country/region is hidden to keep the manuscript anonymous] improved after the completion of this study, additional hardware was purchased by two of the participating schools to increase the training capacity.

Another concern is the gender imbalance among the participants. This means the potential moderation effect of gender could not be examined or partialled out. The imbalance was found in many studies involving participants with ASD, which could be explained by the much lower prevalence rate of ASD among females compared to that among males, based on a meta-analysis and review study (Loomes et al.,2017). In the present study, to utilize resources and maximize the sample size of the study for greater statistical power, only schools which can select at least eight students with ASD and three teachers for training were eligible for participation, whereas the number of girls with ASD was very small (mostly one or two) in each of the schools.

Conclusion

Despite the limitations, this study has clearly demonstrated the effectiveness of the VR-enabled training in enhancing affective expression and social reciprocity of the school-aged children with ASD in a reasonably large scale; and it also pioneered the empirical investigation on the delivery of social skills training using VR headsets at schools. Specifically, it contributes to the field of research and practices in the following ways. First, quantitative evidence supports the use of VR learning scenario, designed based upon Kolb's experiential learning model, in the affective-social skills training for ASD children; such evidence gathered from large-scale empirical studies adopting controlled trials are deemed valuable. Second, this study suggests that by employing virtual agents, the problem of limited support of trainers during the use of VR headsets could be alleviated. Compared to other VR environments or systems, although using the off-the-shelf VR headsets can significantly reduce the technical complexity and increase the accessibility to such interventions at schools, it also limits the delivery of support and facilitation from the trainers. Our study suggested that programme-controlled virtual agents with pre-scripted dialogues can deliver the support and facilitation in VR with minimal inputs from the trainers. With the major limitations mitigated, the emergence of more powerful standalone headsets, such as the Oculus Quest 2, can be used to enhance learning experience in the future. Third, besides the use of off-the-shelf hardware, the training provided to the schoolteachers and professional staffs could enable them to continue to use the VR learning scenarios to train more students. The research team plan to continue with the teacher training implementation and further investigate the long-term sustainability of the project.

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Table 1. The virtual reality learning modules and scenarios.

Learning module	Learning Scenario	General Design	Objective	No. of sessions
1 - Introduction	1. Four Seasons	Open spaces in four seasons of a year with interactable virtual objects and avatars.	Learn to use the controllers for navigation and interaction in the virtual scenes.	2
2 - Executive functioning and daily life skills	2.1. Home	Morning routines at home.	Learn to greet people and practice daily life skills.	3
	2.2. School Bus and Classroom	Riding on a school bus and classroom routines.	Learn to follow directions of caretakers and schoolteachers.	3
3 - Affective skills	3.1. Library	Things to do in a school library, like reading and borrowing a book.	Learn social norms and practice emotion regulation	5
	3.2. Art Class	Art class themed around facial expressions.	Learn emotion recognition and expression	5
4 - Social skills	4.1. Recess	Having leisure time during near the school tuck shop during recess.	Learn reciprocal communication.	5

Learning module	Learning Scenario	General Design	Objective	No. of sessions
	4.2. Physical Education	Having physical education class on the school playground.	Learn to resolve conflicts in the school setting.	5
5 - Consolidation	5. Fun Fair	Fun fair on the school playground with game booths.	Transfer newly gained knowledge and skills to a new context.	2

Table 2. Demographics of the participants.

	Intervention	Control	Intervention vs. Control
	n (%)	n (%)	p-value
Sex (male)	41 (85.4%)	47 (79.7%)	.438
	Mean (SD)	Mean (SD)	
Age (months)	101 (19.9)	112 (19.5)	.004 **
Non-verbal intelligence (RPM)	93 (15.6)	92.5 (16.5)	.879

* p < .05; ** p < .01; *** p < .001.

Table 3. Descriptive statistics of the PEP-3 Affective Expression and Social Reciprocity subscale scores.

	Intervention Group (n=48)		Control Group (n=59)	
	Pre-assessment	Post-assessment	Pre-assessment	Post-assessment
	Mean (SD)	Mean (SD)	Mean (SD)	Mean (SD)
Affective Expression	16.1 (5.16)	18.7 (3.67)	18.7 (3.29)	18.0 (3.97)

	Intervention Group (n=48)		Control Group (n=59)	
Social Reciprocity	18.6 (4.76)	20.4 (3.64)	20.7 (3.18)	19.7 (4.70)

Table 4. One-way ANCOVA results for the post-test score of affective expression considering the pre-test score of affective expression and RPM score as covariates.

Source	Type III Sum of Squares	df	Mean Square	F	p	partial η2
Pre-test	213.7	1	213.7	17.9	.000***	.148
RPM	35.9	1	35.9	3.02	.085	.028
Condition	60.5	1	58.68	5.08	.026*	.047
Error	1227.3	103	11.92			

* p < .05; ** p < .01; *** p < .001.

Table 5. One-way ANCOVA results for the post-test score of social reciprocity by condition using the pre-test score of social reciprocity and RPM score as covariates.

Source	Type III Sum of Squares	df	Mean Square	F	p	partial η2
Pre-test	408.5	1	408.5	30.6	.000***	.229
RPM	28.5	1	28.5	2.13	.147	.020
Condition	72.5	1	72.5	5.43	.022*	.050
Error	1375.7	103	13.4			

* p < .05; ** p < .01; *** p < .001.

Table 6. Mixed repeated measures ANCOVA results for the affective expression score using standardized RPM score as covariate.

Source	Type III Sum of Squares	df	Mean Square	F	p	partial η2
Time × Condition	142.2	1	142.2	15.0	.000***	.126
Error	983.2	104	9.45			

* p < .05; ** p < .01; *** p < .001.

Table 7. Mixed repeated measure ANCOVA results for the social reciprocity score using standardised RPM score as covariate

Source	Type III Sum of Squares	df	Mean Square	F	p	partial η2
Time × Condition	100.3	1	100.3	12.0	.001**	.104
Error	868.2	104	8.35			

* p < .05; ** p < .01; *** p < .001.

Figure 1. Flow diagram of the study.

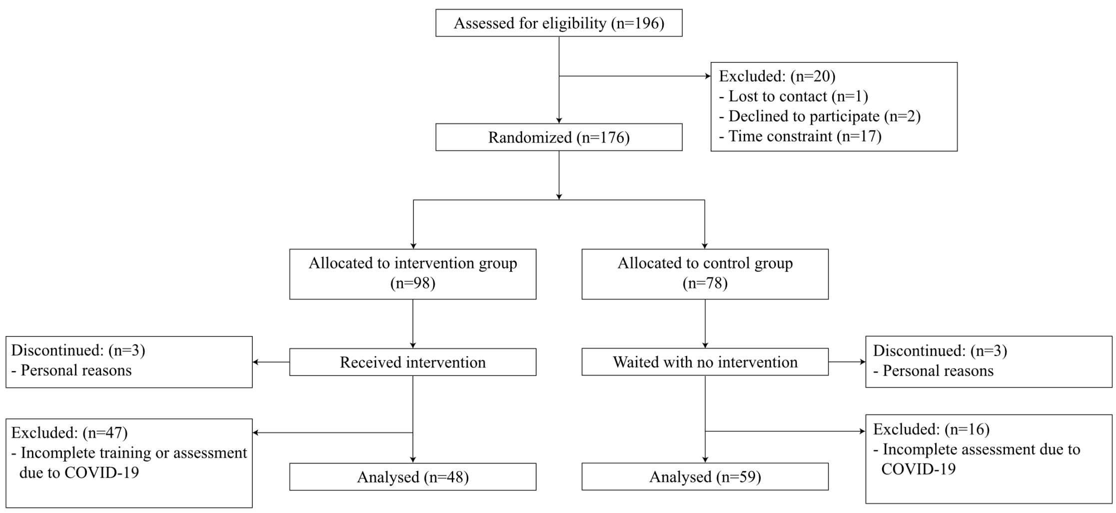
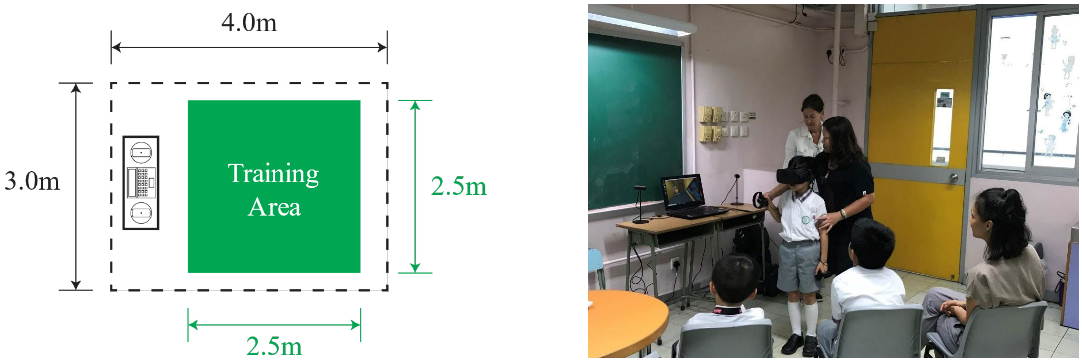


Figure 2. Setting of the training area. (a) Floor plan of the training area in the participating schools. (b) Setup of one of the participating schools.

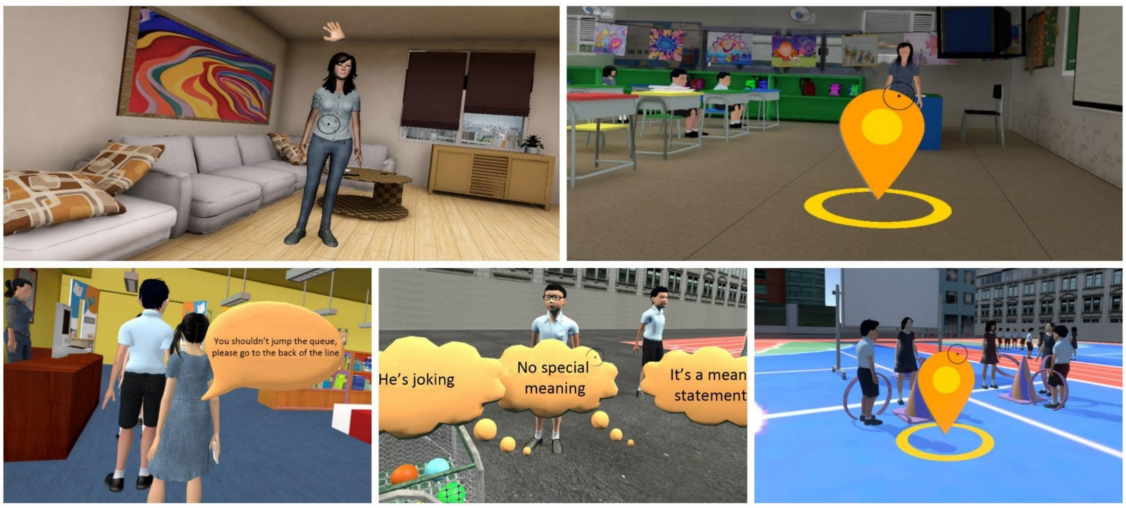


(a) (b)

Figure 3. Screenshots of the virtual reality learning scenarios (All texts were originally in Chinese in the scenarios). (a) screenshots of the eight VR learning scenarios (from top left to bottom right horizontally): Four Seasons, Home, School Bus and Classroom, Library, Art Class, Recess, Physical Education, Fun Fair. (b) social interaction with virtual agents (from top left to bottom right horizontally): greeting, entering a classroom, asking classmate not to jump the queue, expressing own thoughts when encountering verbal bullying, looking for groupmates.


Back
Excited
Sad
Forgot to bring my textbook
OK
Happy
Angry
I probably don't have time to do it.
This is so boring. I'm out.
Points
6

(a)


You shouldn't jump the queue, please go to the back of the line
He's joking
No special meaning
It's a mean
statement

(b)

Figure 4. Plot of the mean scores of the PEP-3 affective expression subscale before and after the experiment across two groups.

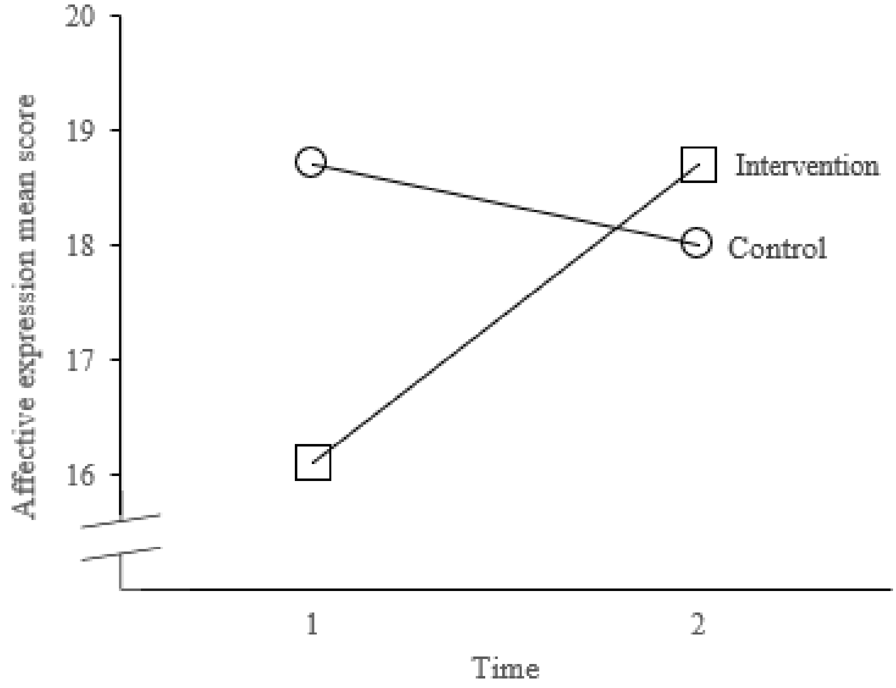


Figure 5. Plot of the mean scores of the PEP-3 social reciprocity subscale before and after the experiment across two groups.