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Designing and deploying a mixed-reality aquarium for cognitive training of young children with autism spectrum disorder

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Autism spectrum disorder (ASD), a developmental disorder severely affecting cognition and social behavior, is increasing in prevalence [1]. This increasing trend is especially severe in children, making the early intervention crucial to ASD treatment. Children with ASD have been found impairments in several aspects of cognition functions. Cognition of children with ASD is characterized by impairments in communication skills and reciprocal social interaction and restricted, repetitive, and stereotyped patterns of behavior and interests. Moreover, children with ASD were found to have attention deficit symptoms such as rapid shifting of attention, delay in shifting attention between visual and auditory stimuli, and impaired attention to the most salient or meaningful feature of a stimulus [2]. Therefore, early training on cognitive ability is very important and essential for the rehabilitation of those young ASD children with cognition impairments [3].

Currently, most clinical interventions are conducted by therapists through oral, behavioral, or picture based guidance. Studies have pointed out that these kinds of interventions are not intuitive or vivid enough to appropriately attract attention, stimulate the interest, or bring positive cognitive outcomes of children with ASD. Some of these interventions may even cause a high cognitive load to the ASD children that leads to the loss of attention. To address this, interventions using computer-assisted technology (CAT) are being increasingly considered. Some studies show that virtual reality (VR) creates a more intuitive, vivid, and immersive interactive environment, which can be potentially used in rehabilitation training for ASD children [4]. Other studies indicate that the VR environment can help maintain ASD children's interest and enthusiasm during training, as well as improving their motivation, concentration, and performance [4, 5]. Although many VR-based CATs were introduced, few of the existing studies leveraged mixed reality (MR) technology to support cognitive training for young children with ASD. Compared with VR-based systems that only depend on the virtual content, MR technology combines both virtual and real worlds, leveraging the advantages of both the real environment and virtual information. Moreover, projective MR systems that do not require on-body equipment were more suitable for ASD children as many of them show a strong aversion to wearing anything on their bodies, such as 3D glasses or head-mounted display.

In this study, we designed and deployed an MR aquarium for the cognitive training of young children with ASD. The system consists of two parts: the physical part and the virtual part. The physical part is a real aquarium with live fish and water plants. The virtual part is a projection display attached at the back of the aquarium, showing the content of the ASD training course. There is an infrared touch screen on the front of the aquarium, composing of infrared emitting and receiving sensing elements mounted on the outer frame of the touch screen, to enable ASD children to interact with the virtual creatures via Multi-Touch method. Our system allows ASD children to (1) take professional cognitive training based on their cognitive characteristics, and (2) experience the fantasy training courses in an aquarium environment, which combines a real aquarium with a virtual underwater world, and also provides simple interaction by Multi-Touch technology (Figure 1).

In a one-month longitudinal study with 20 young ASD children (2.5–5.5 years), we found that our system can effectively improve the performance and positive response of ASD children during training. Results show that the cognitive ability of participants who attend the MR course is better improved than those who do not attend the MR course. Subjective questionnaires also indicate that therapists and parents think the MR aquarium is effective and easy to use, and they hope to bring the MR aquarium home for take-

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(a) (b)

Figure 1 (Color online) Our mixed-reality aquarium and some courses for 2.5–5.5 years old children with ASD. (a) is a scenario of ASD children and therapists using our proposed system; (b) shows some examples of the courses based on the ASD children's cognition characteristics.

home lessons.

Design of mixed-reality aquarium. This system needs to take animal-assisted interventions into consideration and provide professional training courses which are suitable for the cognitive characteristics of young ASD children.

Animals are very effective elements in promoting the cognitive training of ASD children. There are lots of positive influences when using training content based on animals to assist ASD rehabilitation training. Marguerite [6] found a certain effect of calming someone down by observing the aquarium. In the presence of a dog, children with ASD show greater interest and concentration. Gardiánová and Hejrová [7] found that animal-assisted interventions were more effective. Aquarium fish also has positive effects on people's physical and mental health. Observing fish can catch children's focus and has a relaxing effect, and thus it is a suitable way to simulate nature. Therefore, combining animal with CAT is a way to improve training system of ASD.

As an inspiration and exploration in this direction, we develop an MR aquarium system which embeds the professional cognitive training knowledge from ASD therapists. Based on ASD children's cognition characteristics, we work closely with ASD therapists and perform an iterative development to improve the system and course content. We integrate cognitive training courses with the MR aquarium, wherein the training course is visualized and concretized, increasing the interaction between the ASD children, and the training content, as well as between the therapists.

MR system combines a virtual underwater world with a real aquarium. On one hand, we make use of the physical environment of the aquarium with some water plants and swimming real fish as a carrier to attract ASD children; on the other hand, the underwater scene and the sea creatures are modeled in a realistic style to create a more interesting underwater world. And considering that ASD children are generally problematic in their concentration, we choose bright colors when making virtual underwater scenes to better catch their attention. By projecting a virtual undersea world on the real aquarium, a vivid MR training environment can be presented to ASD children.

Natural and simple interactions are of great need to help ASD children learn or maintain an operation. To make it easy for young ASD children to interact with the virtual world, an intuitive and natural interaction is used, i.e., tapping on the surface of the aquarium with the finger. The real-time finger position of each children is captured by the infrared touch screen. Upon receiving the position data, the computer maps it to get the operating instruction, and virtual contents will change accordingly.

Real-time and meaningful feedback can help ASD children pay attention on and understand the knowledge. However, children with ASD have common problems of integration disorders; thereby too much sensory stimulation signals from multiple sources may cause them to behave erratically [8]. Therefore, the feedbacks should not be too much during the training, and we only use instant visual and auditory feedback. Additionally, in order to make it easier for ASD children to get feedback, we check if the selected range is appropriate. These can provide ASD children with a better sense of interaction and can encourage them to be involve in training.

Result. After the training courses are designed and created, we performed a one-month longitudinal study to test how our designed MR aquarium and rehabilitative training course affect the training performance of ASD children. We aim to answer the following two questions in this study.

(1) Understanding the advantages and effects of our MR system on the performance of ASD children during the training.

(2) Understanding the effects of our MR system and course on ASD children's cognitive ability, as well as their linguistic and motor ability.

According to the results of Autism Behavior Checklist and the Chinese version of the psycho-educational profile (third edition) (CPEP3 [2]) combined with a period of clinical observation and discussion made by experienced therapists, a total of 20 ASD children (18 males and 2 females) were selected and completed the experiment. The mean age of the final sample was 45.15 ($\pm$9.19) months. The empirical study involved a design of comparative group having both a pre-test and post-test. The experimental group participated in an MR course, while the control group did not participate. In addition, the two groups participated in some routine training in the hospital (e.g., living skills training etc.), which remained the same between the two groups. The original participants were randomly and equally assigned to the two groups. The major dependent variable was the improvement of cognitive ability. Moreover, the improvements of linguistic and motor ability were also considered as dependent variables. In this study, the training lasted for one month (four weeks). For both experimental and control groups, a systematic assessment of the abilities of participants was performed before (pre-test) and after (post-test) training. The abilities of ASD children were measured with CPEP-3 which is a standardized observation tool for children with ASD from 2 to 7 years of age. Moreover, to evaluate the performance and target-related responses of ASD children dur-

ing the training, we developed a post-training questionnaire and consulted with therapists specializing in rehabilitation of young children with ASD. The questionnaire showed high reliability in this study (alpha = 0.954).

To sum up, after one month of MR course training, the cognitive, language and motor ability of ASD children has been significantly improved. This result basically verified the effectiveness of our MR system in improving the outcome of cognitive training for young ASD children. Moreover, they show that the MR aquarium and its courses indeed have significant potential in the interest development, concentration cultivation and other performance improvement of young ASD children in training. The mechanism of these positive effects and clinical application of this system remain to be explored, and how to balance the impact of the real and virtual world on children is also worth studying in the future.

Declaration This study was carried out in accordance with the recommendations of the Human Research Ethics Committee of Jining No.1 People's Hospital. If this study involved human participants, informed consent was received from each individual. If this study involved human participants, it was conducted in accordance with the 1964 Declaration of Helsinki. If this study involved experiments with animals, it was conducted in accordance with the related institutions' research ethics guidelines.

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Supporting information Videos and other supplemental documents. The supporting information is available online at info.scichina.com and link.springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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