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Beyond reality: Empowering autistic learners in communication

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Abstract

Autistic learners encounter a range of communication challenges in social-emotional communication, non-verbal communication, and building and sustaining relationships. This conceptual paper explores the impact of technology, particularly extended reality (XR), in aiding individuals with autism spectrum disorder (ASD) in enhancing their communication skills. It begins by providing a concise summary of the three main communication obstacles faced by individuals with ASD, and then proceeds to examine various technologies used for ASD education. The primary objective of this paper is to explore the relationship between XR and ASD education through the introduction of a five-component model. It concludes by offering practical recommendations for integrating XR into communication training for individuals with ASD.

Keywords: Autistic learners, Extended reality, Autism spectrum disorder, Communication, Model

Background

UNESCO's recent report disclosed that more than 250 million school-aged children and youth were out of school due to an extensive array of reasons such as poverty, disability, and bullying (UNESCO, 2023). Social equity and inclusion remain critical challenges for educators in modern society. Autistic learners, in particular, may be one of the most susceptible groups to these challenges as they often encounter "persistent challenges with social communication, restricted interests, and repetitive behavior" (American Psychiatric Association, 2024, n.d.). However, the ultimate causes of autism spectrum disorder (ASD) remain unconfirmed by researchers and doctors, though it is generally agreed that both genetic and environmental factors jointly contribute to the etiology of ASD (Hodges et al., 2020).

ASD, according to American Psychiatric Association, 2013, is a developmental disability that may cause communication, behavioral, and social challenges. Among the various challenges, one of the most significant is the lack of sophisticated communicative skills and abilities (Hirota & King, 2023). Previous literature has suggested that individuals with ASD have great difficulties in maintaining conversations through taking turns in conversation and understanding or using nonverbal cues, especially in spontaneous communication (Delaherche et al., 2013; Duffy & Healy, 2011). Notably, the traditional teaching approaches featuring monomodal, memorization, and textbook-based learning may not meet the learning needs of learners with ASD (Banire et al., 2021). As such, researchers and educators have endeavored to explore innovative ways to transform educational practices with ASD students.

X reality (XR), or extended reality, an umbrella term for virtual reality (VR), augmented reality (AR), and mixed reality (MR), has begun to capture the attention of educators, teachers, and therapists (Wu & Lee, 2025). Pegrum and Lan (2023) believe that the XR interface has the affordances of providing 3-dimensional multimodal immersive texts which "add considerable complexity to the creation, interpretation, and exchange of meanings we are used to in 2-dimensional multimodal texts" (p. 2). XR seems to be able to create more immersive learning experiences in order to cater to ASD learners' learning needs. However, the adoption of XR in ASD research has not been widely reported though some attempts were seen over the past decades. This paper therefore aims to cast some light on the possible use of XR for ASD learners. In particular, we present a tentative model for leveraging XR in ASD research.

Communicative challenges of ASD learners

Individuals with ASD typically exhibit deficits in communication and restricted and repetitive behavior (Hirota & King, 2023). According to the diagnostic criteria set out in DSM-5 (American Psychiatric Association, 2013), such deficits in communication and interaction tend to manifest in three main areas: social-emotional communication, non-verbal communication, and the development and maintenance of relationships.

Firstly, in terms of deficits in social-emotional communication, this includes a lack of sharing of interests and feelings, inappropriate social behaviors, difficulty in back-and-forth conversations, and reduced attempts to initiate interaction (American Psychiatric Association, 2013). These deficits can be observed in different stages of development. For example, during infancy and early childhood, there may be a lack of eye contact, reduced or no response to name calling, and low joint attention (Hirota & King, 2023). Young children with ASD may also exhibit limited attempts to initiate communication or a failure to respond to communication initiated by others. Apart from such behavior patterns, individuals with ASD may also have reduced interest in social information. For instance, studies using eye-tracking found reduced interest in social-related stimuli in individuals with ASD. Specifically, when presented with dynamic side-by-side images of social and non-social stimuli (social images of a child dancing vs. non-social pictures of moving geometric shapes), children aged 6-12 years with ASD were found to spend less time looking at the social images compared to typically developing (TD) children (Bacon et al., 2020). Similar findings have also been reported in adolescents and adults with ASD who showed lower preferences for social videos (featuring an actress) compared to non-social ones (of moving objects). Specifically, such adults and adolescents spent less time looking at the social videos compared with individuals with special educational needs but without ASD (Crawford et al., 2016). This difference was also evident when compared with TD individuals (see Chita-Tegmark, 2016 for a meta-analysis). Similar to visual stimuli, a lack of interest toward social emotional communication has also been observed with auditory stimuli. For instance, toddlers with ASD were found to show lower preferences for affective speech (Xiao et al., 2022). When listening to motherese compared to computer-generated sounds, toddlers with ASD showed a preference for the computer-generated sounds and a reduced fixation time for the motherese. This is contrary to the pattern observed in TD toddlers. Further comparison of neural activation patterns revealed reduced activation in the ASD toddlers when listening to higher-affect speech in comparison with the TD group. These findings indicate that the deficit in social interaction and communication can be persistent at different age levels, and communication from varied modalities can be challenging for individuals with ASD.

Such social communication deficits are closely related to language development, which is essential for verbal communication. It has been reported that most children with ASD show delays in language acquisition, with later first words and slower acquisition of speech (Tager-Flusberg et al., 2005). Heterogeneity in language abilities is another marked feature in those with ASD. It is estimated that about 35% of children with ASD never acquire functional language (Gerenser & Schwartz, 2009). However, there are also individuals with ASD whose language skills are comparable with TD children. Compared with TD children, children with ASD show distinct differences in the time course of language development, communication abilities, language acquisition, and language behaviors. Many studies on ASD have looked at the language abilities of autistic children and found that such children show a wide range of reading and decoding skills, while many have difficulties in comprehension and semantic processing (Henderson et al., 2011; Kuhl et al., 2005; Nation et al., 2006; O'Connor & Klein, 2004). Despite varying levels of language abilities, individuals with ASD often also have difficulty in the social and pragmatic aspects of language use. For instance, children with ASD have been reported as achieving lower scores in pragmatic language use, including the appropriateness of initiation, use of context, non-verbal communication, etc. (Reindal et al., 2023). Such skills in children with ASD were also found to be predictive of social communication abilities in adolescence (Miranda et al., 2023).

A deficit in non-verbal communication is another marked feature in individuals with ASD. This includes a lack of eye contact, difficulties in understanding and using gestures and facial expressions, and challenges in processing and using appropriate vocal cues like volume, intonation and prosody during verbal communication (American Psychiatric Association, 2013). Difficulty in emotion recognition has also been reported in individuals with ASD across a wide range of ages (see Harms et al., 2010 for a review). Non-verbal expression of emotions can also be challenging for individuals with ASD. For instance, Northrup et al. (2025) found toddlers with ASD required a longer time to display neutral facial expressions and a shorter time for positive expressions compared with TD toddlers in an emotion elicitation task. Similar differences in non-verbal communication have also been observed in adolescents and adults with ASD. Moreover, Grossman and Tager-Flusberg, (2012) reported a deficit in expressive non-verbal communication in high-functioning ASD adolescents in a series of tasks that measured non-verbal communication abilities. These included production of facial and prosodic expressions, lexical stress, perception of auditory-visual integration, matching of emotional voices with facial expressions, and repetition of facial expressions. Their results revealed a different pattern between ASD and TD groups in expressive non-verbal communication. Specifically, for higher functioning adolescents with ASD, the use of non-verbal communication skills was more challenging than perceiving non-verbal information.

The deficit in social communication can be explained by weakness in Theory of Mind (ToM) skills (Baron-Cohen et al., 1985; Prelock & Nelson, 2012). ToM skills refer to the ability to understand the mental states of other people including intentions, beliefs, and desires. This ability plays an important role in social perception and interaction during development from infancy to adulthood (Rakoczy, 2022). During early childhood, children typically develop fundamental ToM skills that support early social interaction. Tasks used for measuring these skills include: the false belief task, which requires the ability to distinguish perspectives from different agents and predict their actions; and the appearance-reality task, which requires knowledge and understanding from different perspectives of what an object looks like and how it really is (Rakoczy, 2022). ToM skills can be measured in different ways in both parent ratings and verbal tasks. This often includes the ability or knowledge to understand beliefs, intentions, or feelings that are different from the child's own perspective, and the ability to imagine another person's perspective in a created context (Rosello et al., 2020). Studies use parent ratings that measure the different levels of ToM skills, which include the understanding of emotions, distinguishing social and physical representations, and making inferences and social judgments (Baixauli-Fortea et al., 2019). ToM skills in individuals with ASD can also be heterogeneous. For instance, Rosello et al. (2020) identified two subgroups of children with ASD based on their performance in ToM tasks. The subgroup with higher ToM skills demonstrated higher levels of pragmatic skills and adaptive behaviors. There are also differences in the levels of ASD severity in the social and communication domains.

ToM skills also have an impact on language abilities. For example, better ToM skills have been found to correlate to the ability to comprehend idioms after controlling for the language abilities in children with ASD, but not in TD children (Whyte et al., 2014). Researchers have also examined ToM skills in high-functioning children and adolescents with ASD and found that such individuals were able to achieve similar levels of advanced ToM skills, although they may have difficulty applying them in real-life scenarios (Scheeren et al., 2013). Findings from an intervention study also showed that after ToM training, children with ASD were found to have improved ToM skills at the conceptual level, although their social behavior based on parent and self-reporting did not improve (Begeer et al., 2011). These findings suggest that children with ASD can acquire ToM skills, and be provided opportunities to practice these skills in every day life scenarios.

To summarize, communication deficits in individuals with ASD can manifest in various ways, including early social visual and auditory attention, verbal and non-verbal communication, as well as the application of ToM skills in social communication and interaction. In addition, individuals with ASD can display heterogeneity in terms of cognitive skills, language abilities, and language development trajectories. Therefore, it is essential to consider the communication difficulties of individuals with ASD from a multidimensional perspective. Technologies that incorporate visual and auditory information to create social communication scenarios can be beneficial in providing training and support to individuals with ASD.

ASD and technology-enhanced learning

Various assistive technologies have been experimented with ASD learners to improve their communication skills over the past decades. First, mobile technology has been widely discussed in the past decade. Among others, the Apple iPad seems to be a popular tool. For example, Xin and Leonard (2015) utilized a speech-generating device application in the iPad to facilitate three 10-year-old learners with ASD from the USA. Over six weeks of learning, the participants demonstrated progress in initiating requests and responding to questions. Likewise, with a single case study of a 13-year-old ASD learner from Canada, Desai et al. (2014) confirmed the positive effects of the iPad technology with regard to the improvement of social communication skills, especially with the increase in learning interest.

However, the use of iPads does not always lead to immediate, positive effects. In England, Fletcher-Watson et al. (2016), for example, compared and contrasted the learning situation between a control group and an intervention group that made use of iPads in learning. The results showed that no significant differences were found in the intervention group, though parental attitudes were welcoming. One possible explanation was the lack of sufficient pedagogical support from teachers to leverage technology in a more pedagogically sound manner. As such, on a more theoretical level, Boyd et al. (2015) put forward five general criteria for educators and teachers when adopting iPad technology for communication training, including customized content, user-friendly design, sufficient teacher guidance, research-based apps, and affordance costs.

Lately, the use of robots and intelligent systems has also started to capture researchers' and educators' attention, especially with the popularity of artificial intelligence (AI) technology. For example, based on the concept of serious games, Bernardini et al. (2014) developed an intelligent agent to provide customized feedback to 29 primary school ASD learners in the UK. The authors highlighted the importance of believability, decided by the adaptability of agents to respond or adjust to learners' learning needs.

To illustrate the development of intelligent tutoring systems, Aljameel et al. (2019) detailed the process of a learning system for 24 young ASD learners whose first language is Arabic. Results indicated the kinesthetic, visual, and auditory learning styles had advantages in enhancing learners' Arabic learning performances.

Focusing on job interviewing training, Kumazaki et al. (2019) developed a robot to support ASD adults in the job market with participants from Japan. Especially with feedback and nonverbal cues from the robot, the young adults demonstrated improvement in nonverbal communication skills and confidence.

Gu et al. (2025) conducted a scoping review examining the application of AI in enhancing conversational skills among autistic learners. According to their review, existing AI chatbots primarily relied on rule-based response generation methods that generate pre-determined answers, which limited their ability to provide personalized and flexible responses – a key requirement for supporting autistic learners. The review also suggested that the potential of generative AI (GAI) technology to improve emotional recognition and expression skills remains largely unexplored. One notable exception is the work of Tang et al. (2024), who developed a GAI-powered chatbot. In their study, the tool showcased promising results, assisting 15 autistic children in developing emotional and communicative abilities while also serving as a mediator between the children and their parents.

Though AI robots and chatbots have the educational potential of providing customized, interactive learning experiences, they may not be able to offer immersive learning experiences (Gu et al., 2025), which are essential in meeting the unique learning needs of learners with ASD. As such, immersive technologies such as XR should also be taken into account so as to better facilitate communication skills.

ASD and XR research

a) Virtual reality

Existing studies have proven the positive role of VR in facilitating ASD learners in behavioral, cognitive, social, and affective domains (e.g., Didehbani et al., 2016; Kandalaft et al., 2013; Lorenzo et al., 2016). In essence, VR simulates the real world or creates entirely new worlds for users. Differing from the monomodal, spoon-fed style of learning, VR has been argued to have unique features of immersion, interactivity, authenticity, and gamification (Wu et al., 2023; Wu, Zhang, Lee, 2024). Furthermore, Godwin-Jones (2023) remarks that with avatars ASD learners may be offered a less anxious, safer learning environment, where anonymity plays a central role.

Since the 1990s, researchers and educators have made attempts to contribute to ASD studies with the early generation of VR equipment. One classic example was Strickland et al. (1996), who reported two ASD children's perceptions of using heavy VR helmets in learning. This pioneering study suggested the learners showed positive attitudes toward the integration of immersive VR through active participation. However, the first generation of VR had various challenges such as bulky equipment, low resolution rate, and high costs, which to a large extent prevented learners and teachers from adopting this new technology into ASD treatment (Brooks, 1999).

Due to the fast evolution of VR technology, the use of VR in ASD inclusion has been burgeoning over the past two decades. Several studies have reviewed the developmental trends of VR in ASD research. The mini-review by Bellani et al. (2011) revealed that most of the previous VR and ASD studies employed desktop VR, involving a monitor and a mouse to navigate the simulated virtual world. In addition, the prior studies had the feature of limited duration of experiments and a small number of participants. Yet, these early studies provided preliminary evidence for using VR to enhance ASD learners' emotional responses, social interactions, and imaginative skills.

Mesa-Gresa et al. (2018) reviewed 31 VR studies with ASD participants. Their review suggests that daily living skills and communicative skills, including social and emotional skills, have been extensively reported among the reviewed studies. They pointed out that the use of VR has been quite constructive for its "therapist-controlled and safe environment" (p. 11), which further allows therapists to understand and analyze ASD learners' behavior and therefore provide more customized support. Compared to early research in the 1990s, another major benefit highlighted is the low-cost VR technology these days. VR learning has been extended beyond the classroom and ASD learners can make use of different VR platforms at their home with the support from their parents. However, based on the review, previous research still shared the common shortcomings of a small number of participants and an unbalanced gender ratio among the participants.

More recently, Bravou et al. (2022) reviewed the latest research on ASD and VR from 2015 to 2021. They reported that the reviewed studies focused largely on the improvement of emotional skills and social communicative skills through immersive VR. It is argued that since many technical barriers have been overcome, VR has been seen as more beneficial to ASD learners.

b) Augmented reality

In contrast to VR, AR represents an innovative method for improving ASD learners' communicative abilities. AR overlays virtual elements onto users' physical environment, offering features such as interactivity, authenticity, and user-friendly interfaces. By reviewing 13 existing studies, Cheng and Bololia (2024) discovered the utility of AR in bolstering ASD learners' communication, such as the improvement of nonverbal communication, the recognition of facial expressions, the increase in attention levels, and the fostering of basic social interactions. However, this line of research is at a premature stage, where further exploration is needed to attain a more conclusive understanding. Below, we review some of the latest empirical studies of using AR in augmenting ASD learners' communicative proficiency.

Lorenzo et al. (2019) conducted a quasi-experiment study to investigate the impacts of AR on 11 learners with ASD in Spain. Interestingly, both the control and experimental groups did not exhibit significant differences following their participation in learning activities with and without AR. Despite this, some improvements in communicative skills were reported for both groups. However, the study did not offer the in-depth reasons underlying the lack of significant disparities.

By utilizing an AR video-based storybook, Chen et al. (2016) observed a positive outcome among six Taiwanese ASD adolescents in terms of their enhanced capabilities in recognizing and interpreting emotions from facial expressions. This study highlights the importance of making the best of multiple sensory modalities to capture and sustain the attention of learners with ASD.

Another recent study by Liu et al. (2017) introduced their smart glasses-based AR system that effectively trained two ASD children to enhance their social skills, especially in non-verbal communication. They maintained that AR provides "visual and auditory cues while the user is simultaneously engaged in natural or structured social interactions" (p. 6). In other words, AR technology, with its multisensory nature, has the potential to address communication difficulties by compensating for the challenges associated with recognizing and managing contextual cues during interactions.

As a novel exploration, Lee (2021) created AR characters in real-time interactions with ASD learners. This unique approach suggested the necessity of roleplay in improving ASD learners' communicative skills. The interactivity and fidelity of the AR characters elevated learners' interest and attention levels, underscoring the potential for developing innovative learning tools that replace the traditional role-play with AR technology to optimize learning outcomes.

c) Mixed reality

MR integrates AR and VR, allowing users to interact with virtual elements in the physical world or with physical elements in the virtual world. One initial pedagogical attempt was undertaken by Crowell et al. (2020), who compared the effects of MR and LEGO on collaborative and social interactions. The study found that social initiation skills were significantly improved for MR groups although no statistical differences in anxiety levels were observed. Yet, we have only seen a limited number of empirical studies that made use of this new technology in ASD education. The development of MR technology is still in its infancy, restraining its large-scale implementation in education (Pellas et al., 2020).

A model of ASD and XR learning

The intersection of ASD and XR introduces a transformative approach to education and therapy. XR technologies, including AR, VR, and MR, can provide distinct opportunities for creating tailored learning environments for individuals with ASD. By synthesizing the previous sections, this section proposes a model to integrate XR into ASD education (Figure 1) that emphasizes five important elements and how they work together to serve the three major communicative needs of ASD learners outlined in the section "Communicative challenges of ASD learners".

a) Sensory regulation

As previously discussed, many individuals diagnosed with ASD often experience difficulties in sensory processing and non-verbal communication. This means that they have challenges in regulating and interpreting sensory stimuli, which are vital to effective interpreting and using non-verbal cues in communicative tasks. XR has demonstrated potential in supporting ASD learners in managing and regulating sensory experiences. Restrepo et al. (2024) emphasized that XR can provide controlled and predictable sensory stimuli, which can be particularly beneficial for learners with ASD. By incorporating multisensory inputs like haptic, tactile, kinesthetic, and olfactory feedback, XR technologies can create more immersive and engaging learning environments that may increase ASD learners' interest.

The utilization of XR technologies has the potential to enhance the sense of presence, engagement, and self-efficacy among ASD learners, creating a new way to interact with their surroundings. As mentioned, ASD learners do not seem to appreciate affective speech like TD learners. VR, for instance, can recreate calming and soothing environments,

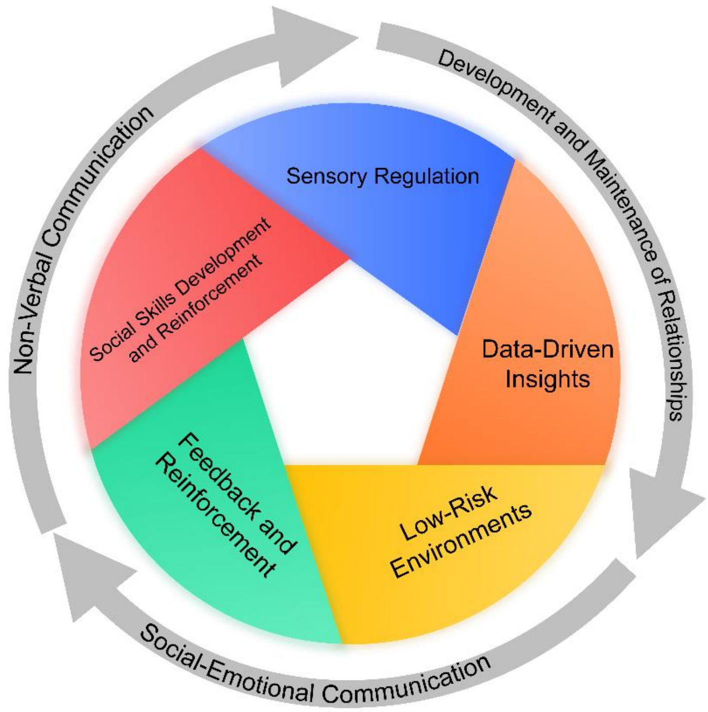

Fig. 1 A model of ASD and XR learning

providing individuals with ASD an opportunity to experience sensory input in a controlled and less overwhelming manner. AR overlays useful information and cues onto real-world settings, aiding individuals in navigating their environments and reducing sensory overload while improving their focus.

A recent study by Johnston et al. (2020) demonstrated the positive impact of XR technologies on individuals with ASD. The study invited six ASD learners to utilize *SoundFields*, an interactive virtual reality game, and reported that the realistic 3D auditory stimuli effectively simulated the movement and acoustic environments of feared sounds. It facilitates ASD learners to experience and desensitize themselves to challenging auditory stimuli.

b) Data-driven insights

Apple's launch of the Vision Pro is seen as the potential start of a new era connected to the Metaverse realm, closely tied to the utilization of XR technology and AI. While still in early phases, XR platforms are being developed to integrate AI features by utilizing vast datasets to gather detailed information on user interactions, progress, and behaviors. These data can then be analyzed to extract personalized insights into learning patterns, leading to customized adjustments in learning environments and methodologies. Educators can leverage these insights to create tailored interventions aimed at maximizing individual achievement. For instance, Song et al. (2024) introduced the *LearningverseVR* platform, which includes AI-driven non-player characters in an XR setting. In another instance from the U.S., Divekar et al. (2022) developed the *Cognitive Immersive Language Learning Environment* (CILLE) in learning Chinese by blending XR technology with AI Agents that exist in the panoramic screen, providing conversational roleplay in diverse scenarios. Students engage with these agents using various modes like voice, gestures, and text transcriptions generated by automatic speech recognition.

In the field of ASD education, limited examples have been identified. A recent exemplar study by Schmidt et al. (2023) showed the utilization of the immersive VR platform *Virtuoso* by six ASD adults from the U.S. to train their abilities in using public transportation. Yet, to date, there is little work on using sophisticated XR platforms to use big data or AI to facilitate the development of communicative skills in ASD learners. This area warrants greater attention from ASD educators and teachers, as data-driven insights can offer tailored and prompt feedback to student learning. Moreover, in conjunction with the utilization of large language models like ChatGPT, ASD educators should collaborate in the creation of more specific models tailored for ASD learners with technicians. For example, since ASD learners tend to experience linguistic challenges in semantics and pragmatics, XR platforms integrated with AI can offer more personalized communicative practices for this population of learners so as to prepare them for the real-world interactions.

c) Low-risk environments

In contrast to the traditional textbook-based, exam-oriented, and teacher-fronted instruction, the incorporation of XR in mainstream education has been recognized for its benefits in creating safer environments, which helps to lessen learning anxiety and boost learning motivation (Wu & Lee, 2025). Similar advantages have been noted for ASD learners (Mesa-Gresa et al., 2018). According to Schmidt et al. (2024), XR has the unique affordance of making ASD learners "feel at ease and calm by creating stable and unchanging surroundings" (p. 1815) since the virtual world can 1) facilitate concentration and minimize real-world distractions, 2) shield learners from the consequences of mistakes or embarrassment, and 3) provide a secure learning setting. Similarly, AR (e.g., Abdullah et al., 2024) and MR (e.g., Sayis et al., 2022) researchers have emphasized the importance of predictable contexts in reducing anxiety and increasing confidence in ASD education.

Furthermore, Ward and Esposito (2019) argued that interactions with avatars and the provision of immediate feedback in a non-threatening manner further supports a low-risk environment for ASD learners. Their study demonstrated that 12 high-functioning ASD adults in the U.S improved their self-efficacy in managing difficult situations during VR job interviews.

Thus, XR provides unique opportunities for autistic children to develop their ToM - understanding others' thoughts and feelings—within a safe and controlled context. Children can engage with avatars or virtual peers in social scenarios that simulate real-life interactions without the immediate pressures or potential social pitfalls of the physical world. This allows them to experiment with different social cues and responses, enhancing their ability to interpret and predict others' behaviors. For example, XR can present scenarios where children must identify emotions expressed by avatars, enabling them to practice perspective-taking in a low-stakes setting. The immediacy of feedback within these environments further reinforces learning, as children can receive guidance on their social interactions without fear of judgment. By fostering this type of practice, XR not only supports the development of ToM but also contributes to building social confidence, making these technologies invaluable tools in the education of autistic learners.

d) Feedback and reinforcement

XR technologies deliver immediate and personalized feedback, which is crucial for overcoming the socio-emotional challenges of ASD learners. Wu, Yang, et al. (2024) proposed that the features of XR technologies can be aligned with the need to provide uptake of feedback, where learners may become more willing to make use of feedback as feedforward to improve their future learning. In real-world situations, ASD learners have reported challenges in navigating multimodal communication, and in traditional, bricks-and-mortar classroom setting, they tend to receive less training in multimodal interactions (Mosher et al., 2022). This lack of preparation can result in anxiety and unwillingness to communicate when they encounter real-world scenarios. Rather than placing ASD learners directly into the unpredictable nature of the real world, XR offers a solution by simulating authentic interactive social situations and stimulating ASD learners' multiple senses. By providing multimodal feedback, XR goes beyond textual communication, thereby reducing comprehension difficulties for ASD learners.

Moreover, learning in an XR environment can also facilitate timely feedback from various sources, including peers, teachers, avatars, and the virtual environment. In Didehbani et al.'s (2016) study, 30 ASD children appreciated the immediate feedback they obtained from a virtual coach throughout their social cognitive training in an XR setting. More than often, XR learning is intertwined with game-based learning (Wu et al., 2025). Incorporating gaming or gamification elements into the XR environment "facilitate comprehension of the subjects taught, allow students to be more focused, and increase their curiosity and imagination" (Lampropoulos & Kinshuk, 2024, p. 1768) and allows learners to become more emotionally receptive to feedback, whether it be positive or negative. Though limited research evidence so far, current studies suggest that this approach enhances engagement and motivation, making learning experiences more enjoyable (e.g., Ramos Aguiar et al., 2023).

e) Social skills development and generalization

XR environments enable the simulation of low-risk social scenarios, offering a secure and controlled setting for learners to develop and practice social skills. For ASD learners, this can be advantageous as they can enhance their social abilities through guided interactions in XR, boosting confidence and motivation. A major hurdle for ASD learners is skill generalization across different contexts. XR can address this by simulating various real-world environments where acquired skills can be applied. For instance, an XR scenario might mimic not only a classroom, but also an amusement park, a zoo, or a workplace, allowing learners to practice in a variety of contexts.

Mosher et al. (2022) reviewed 41 ASD educational studies utilizing XR and reported significant improvements in social skills in 15 of these studies. Additionally, skill generalization was observed in most of the reviewed studies. They argued that XR learning can empower ASD learners to transition more smoothly into real-world environments, specifically noting that “AR would allow … interactive [experiences] in the real-world environment through visual, auditory, and haptic feedback” (p. 347). In addition, Roberts et al. (2023) reviewed 17 ASD studies using XR from five databases. They reached a conclusion that using XR for ASD learning is in its infant stage and no affirmative conclusions have been reached or generalized.

Lee et al. (2018), for example, developed an AR-based training system with a feature of 3D models of avatars and a combination of physical and virtual content. Three ASD children who used this system reported that the process of mastering social skills became more interesting, interactive, and incentive. The technology improved the understanding of ASD learners with 3D, multisensory environment. Yet, they argued that this is a new field with little understanding and more research effort should be invested. Another example is provided by Ip et al. (2018), who designed a VR program (http://aimtech.cityu.edu.hk/vpad2/vr_en.html) for enhancing the social skills for ASD children through diverse scenarios such as the four seasons, library, school bus, and tuck shop. In each scenario, learners are supported to become familiar with the daily situations, practice basic social skills, and consolidate these skills by transferring or generalizing them to other contexts. Over a 14-week period, 94 ASD students demonstrated improvements in their “emotion expression and regulation, and social interaction” (p. 11) and highlighted the necessity of repetitive exposure and practice when designing XR activities for ASD learners.

Operationalization of the model in real-life education

This section examines the abovementioned VR program developed by Ip et al. (2018) which was designed to support children with ASD in developing essential social and emotional skills through immersive, scenario-based learning. By retrospectively applying the five-component framework outlined in our model (Figure 1), we illustrate how such XR interventions can be structured to meet the unique needs of ASD learners.

a) Sensory regulation

One of the core challenges for ASD learners involves managing sensory stimuli. The VR system designed by Ip et al. incorporated a range of sensory inputs—such as background environmental sounds (e.g., chatter in a school cafeteria or the hum of a library) and nuanced visual elements (e.g., facial expressions and gestures of avatars)—to create a controlled, immersive experience. These environments allowed learners to gradually become accustomed to sensory-rich contexts at their own pace. This closely aligns with the sensory regulation component of our model, which advocates for XR settings that are adaptable and predictable, thereby minimizing sensory overload and promoting tolerance. The study observed increased sensory resilience among participants, lending empirical support to this aspect of the model.

b) Data-driven insights

While the original implementation did not feature advanced AI or machine learning analytics, the program still facilitated basic data capture—such as tracking learner interactions and responses to social prompts. Educators could use this data to observe behavioral patterns and tailor instructional support accordingly. This reflects the data-driven insights component of the model, which envisions XR platforms as capable of generating actionable feedback loops through user data. With future enhancements, this element could be expanded to include real-time adaptive learning pathways powered by AI, enabling dynamic personalization of content and pacing (Lee et al., 2026).

c) Low-risk environments

A defining strength of XR in ASD education is the creation of safe, consequence-free environments for social rehearsal. The VR program offered learners the opportunity to engage in simulations such as ordering food at a tuck shop or interacting with peers on a school bus. These scenarios allowed repeated practice without the pressure of real-world repercussions, reducing anxiety and increasing learner confidence. This directly corresponds to the model's third component, which emphasizes the importance of low-risk environments where learners can experiment with social behaviors and self-correct without negative consequences. The study reported increased learner willingness to engage socially, highlighting the psychological safety such environments can provide.

d) Feedback and reinforcement

Timely and structured feedback was embedded into the VR system via virtual coaches and visual cues. For example, if a learner failed to initiate a greeting, the system would prompt a corrective suggestion or demonstrate an appropriate response. This aligns with the feedback and reinforcement component of our model, which stresses the necessity of consistent, multimodal feedback to support skill acquisition. Ip et al. (2018) found that learners demonstrated improved performance in areas such as emotion recognition and conversational turn-taking, affirming the efficacy of feedback-rich XR environments.

e) Social skills development and generalization

To promote generalization, the VR program exposed learners to varied social contexts that mirrored real-life settings. Skills practiced across different scenarios—such as maintaining eye contact, understanding personal space, and managing transitions—helped facilitate transfer to real-world interactions. This reflects the final component of our model, which emphasizes the design of XR experiences that support the bridging of virtual practice with real-life application. Follow-up assessments in the study indicated that learners not only retained the targeted skills but were also able to apply them outside the virtual context, demonstrating effective generalization.

The VR intervention by Ip et al. (2018) provides a compelling, real-world example of how the proposed five-component model can be operationalized in the design of XR applications for ASD education. Each facet of the program—from its sensory scaffolding and iterative feedback to its support for data-informed instruction and real-world transfer—maps coherently onto the model's structure. This alignment supports the model's relevance and practical utility in guiding the design of inclusive, adaptive XR learning environments. Future developments could further extend its capabilities by incorporating AI-driven personalization and expanding the application of augmented or mixed reality for greater contextual diversity.

Conclusion

Our proposed model harnesses the advantages of XR technologies to create a flexible learning framework for individuals with ASD. By focusing on sensory management, social skill development, skill transferability, data-driven feedback, and insights, this model aims to enhance educational and therapeutic experiences for ASD learners, fostering greater independence and achievement. This innovative approach not only addresses the specific challenges faced by ASD learners but also lays the groundwork for more inclusive and effective educational methods.

However, just as other models, future research is in need to verify the effectiveness in ASD education. In advancing this model, we encourage readers to consider the following challenges in designing XR experiences for ASD learners:

1) Technical Barriers: As XR technologies evolve, supporting ASD learners in navigating technical issues is crucial, highlighting the importance of educator training. *Suggestions*: Creating XR interfaces that are friendly for individuals with ASD is crucial. These interfaces should feature intuitive controls and require minimal setup, making them accessible for ASD users. Additionally, having open-access repositories to help troubleshoot common technical issues would enable educators and parents to independently solve problems as they arise. This empowerment can significantly enhance the usability and effectiveness of the technology in educational settings.
2) Technology Acceptance: This involves not only learners' acceptance but also the perspectives of teachers and parents regarding the adoption of new technologies. *Suggestions*: This issue could be tackled by normalizing new technologies through their integration into different areas of school learning. Just as students became accustomed to using PowerPoint presentations two decades ago, users need to move past the novelty of new technologies before they can be fully integrated into regular use. Additionally, conducting longitudinal studies to evaluate the long-term implementation of XR with diverse learners on the autism spectrum can help persuade various educational stakeholders of its benefits.
3) Novelty Effect: Maintaining the interest and motivation of ASD learners in XR environments is a known challenge, prompting educators to explore strategies that encourage autonomous learning. *Suggestions*: Future directions focus on creating adaptive XR systems that grow and change alongside the ASD learner's progress. These systems should feature dynamic content updates and personalized challenges tailored to individual needs. Additionally, incorporating gamification elements—like rewards and progress tracking—can help maintain motivation and keep ASD learners engaged.
4) Physical Discomfort: Addressing potential physical discomfort from XR use is vital, especially for ASD individuals. Opting for semi-immersive or non-immersive VR experiences, instead of immersive VR with heavy headsets, could be beneficial. *Suggestions*: Solutions include prioritizing lightweight, comfortable hardware and providing customizable sensory settings, such as adjustable brightness and sound levels. Additionally, considering semi-

immersive or non-immersive virtual reality options, like tablet-based augmented reality, can help alleviate physical strain.

5) Teacher Education: Comprehensive training for educators is essential for integrating XR into ASD education. Teachers should be equipped to handle software selection, design XR-based activities, nurture metacognitive and cognitive strategies, and manage unforeseen challenges in XR learning environments. *Suggestions*: Future efforts will focus on partnering with XR developers to design training modules for teachers that emphasize selecting the right software, creating engaging activities, and incorporating metacognitive strategies (Lee & Wu, 2024). Establishing professional learning communities can promote collaboration among educators, allowing them to share insights and best practices. It is essential to bridge the divide between technologists, educators, and clinicians to achieve this.

   One effective approach is to form interdisciplinary teams that can work together to co-design XR tools that meet both educational and therapeutic objectives. Additionally, hosting conferences and launching joint research initiatives can further encourage these collaborative efforts, creating a more integrated approach to using XR in teaching and healthcare.

In conclusion, addressing the educational challenges faced by autistic learners requires innovative approaches that go beyond traditional methods. Our exploration into the potential of XR technologies offers a promising avenue for creating immersive and adaptable learning environments tailored to the unique needs of ASD students. With careful implementation and ongoing research, XR has the potential to transform the educational landscape, ensuring that autistic learners are equipped with the tools they need to thrive in a diverse and ever-evolving world.

Abbreviations

ASD: Autism Spectrum Disorder; XR: extended reality; VR: virtual reality; AR: augmented reality; MR: mixed reality; AI: artificial intelligence; GAI: generative AI; ToM: Theory of Mind; TD: typically developing; DSM-5: Diagnostic and Statistical Manual of Mental Disorders, 5th edition; UNESCO: United Nations Educational, Scientific and Cultural Organization; CILLE: Cognitive Immersive Language Learning Environment.

Authors' contributions

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Not applicable.

Declarations

Competing interests
The authors declare that they have no competing interests.

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