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REVIEW PAPER

Immersive Technology to Teach Social Skills to Students with Autism Spectrum Disorder: a Literature Review

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Abstract
This study presents the findings of a systematic review of empirical research on the use of augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR) to present social skill instruction to school-age students with autism spectrum disorder (ASD). Forty-one articles met the inclusion criteria. Studies targeted relationship skills, emotion recognition, social awareness, cooperation, and executive functioning. The intervention caused statistical improvement in 15 of the 41 studies (37%). Practitioners, parents, and researchers reported significant improvement of social skills in 32 studies (83%). We suggest modifications to the technology and interventions within the technology which may increase statistical gains for students. We conclude with recommendations for researchers and practitioners implementing AR and VR delivered social skill interventions.

Keywords Virtual reality · Augmented reality · Social skills · Autism spectrum disorder · Systematic review

Students with autism spectrum disorder (ASD) often express social interests (Cheng et al., 2010) and actively seek out relationships. However, a lack of understanding of the rules of social behavior frequently results in isolation. According to the American Psychiatric Association (2013), children with ASD display persistent difficulty in "social communication and social interactions across multiple settings" (p. 51). If not addressed, adults with ASD display limited engagement with others which places them at high risk for anxiety and depression (Hollocks et al., 2019). These social communication and interaction challenges complicate relationship development and maintenance for students with ASD (Cacioppo & Cacioppo, 2014).

Poor social competence is linked to unemployment and underemployment (Tobin et al., 2014). According to the National Autistic Society (2016), 85% of adults with ASD are unemployed and only 3% live independently. Employment and independent living status are directly linked to healthcare costs (Chen et al., 2015) and associated with high per capita costs of serving individuals with ASD in the USA (Knapp & Mandell, 2012). Improving social competences and skills in students with ASD may improve employment and overall quality of life. This problem has prompted some researchers to investigate technology-based interventions to improve social outcomes for individuals with ASD. One promising intervention type focuses on the use of digital depictions of realistic environments through immersive technology.

Augmented reality (AR), virtual reality (VR), mixed reality (MR), and extended reality (XR) provide realistic, immersive instruction that has the potential to improve social competence and skills for individuals with ASD. AR, VR, MR, and XR are all relatively novel but increasingly available forms of technology. AR enhances the real world by overlaying digital content on real-world elements and often provides the user with a feeling of something tangible being placed in one's environment. AR contains both an aspect of technology and the physical world and with modern technology may include text, audio, video, QR codes, links, and interactive 3D models.

VR provides a digital simulation of an environment which is often three dimensional where a person physically interacts with technology and is immersed in such a manner that the senses perceive a "real world." VR often involves a head-mounted display (HMD) such as an Oculus Rift or HTC Vive. VR may involve older technology such as 3D glasses inside a Cave Automatic Virtual Environment, which is a

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virtual environment (VE) with three to six projectors directed on the walls, floor, and ceiling of a small room. MR combines technologies into a continuous scale of VR and AR which allows the user to interact with and manipulate physical and virtual elements.

VR and MR may use non-immersive or immersive environments. A non-immersive environment usually has 3D properties or aspects that appear real on a screen but does not block out a person's true environment (Carreon et al., 2020). Conversely, an immersive environment is intended to replicate ordinary sensory experiences and often involves the use of head-mounted displays, Cave Automatic Virtual Environment, or blue screens that attempt to block out the real environment and promote synthetic experiences. XR is an umbrella term referring to all real-and-virtual combined environments and areas generated by wearables. XR takes massive amounts of detailed and personal data (i.e., a person's emotions, likes, interests) and synthesizes this information to make a virtual experience even more indistinguishable from a real experience. XR is essentially MR that is further connected, intelligent, and immersive.

AR, VR, MR, and XR were developed to allow users to have experiences that may otherwise not be available such as visiting a different country or dissecting the human brain. Students with ASD may benefit from this technology because it provides opportunities for practice in an environment which mimics an authentic environment where the skill would be applied. Researchers report that VR not only provides a practice environment but also constrains viewing areas and auditory input which helps students with ASD focus on relevant stimuli (Charlop-Christy & Daneshvar, 2003).

Miller and Bugnariu (2016) reported VR to provide specialized curriculum content with increased standardization of procedures, decreased social pressure, increased opportunities for practice, and increased student motivation. Cheng et al. (2010) reported AR provides increased opportunities for practice with reduced social pressure for students with ASD. Parents and educators of children with ASD report more positive social interactions generalized into their environments from virtually delivered social skill interventions than traditional instruction from humans (Miller & Bugnariu, 2016; Stichter et al., 2014). Therefore, AR, VR, MR, and XR should be further explored in order to understand their ability to provide systematic and individualized social skill instructional practices for students with ASD.

Prior Reviews of Literature

Researchers have examined the effects of innovative technologies to deliver instruction, but often focused on the student's ability to use and navigate the technology (i.e., usability studies). In one literature review (Kurilovas, 2016), which focused on MR environments, researchers were primarily interested in the quality and personification within the learning environments and found improved student motivation and satisfaction. Researchers did not investigate the effectiveness of the technology in teaching or learning. Systematic reviews using MR by implementing both AR and VR for instruction (Sheik-Ali et al., 2019) solely considered the technology in terms of surgical education in the medical field. Even with the limited evidence base, research reveals that AR and VR are currently used in general education classrooms (Garzón & Acevedo, 2019), and XR is predicted to be mainstreamed in schools and businesses within the next 5 years (Scribani, 2019).

Virtual and augmented technologies offer significant advantages for enhancing classroom learning (Hew & Cheung, 2010; Mikropoulos & Natsis, 2011; Rajendran, 2013). Radu's (2014) meta-analysis found AR in educational settings improved math and science content recall, collaboration, long-term memory retention, and motivation for both below average and average students. However, they also reported high achieving students did not display the same benefits from AR as lower achieving students. Howard and Gutworth (2020) focused on the effects of VR on social skills for typically developing students and found VR training to be more effective than comparison programs by almost three-fourths of a standard deviation. The above studies focused primarily on technology characteristics such as gaming elements and level of immersion rather than student characteristics. The studies did not discuss methods used within the technology to guide student learning.

Bellani et al. (2011) reviewed studies that applied virtual technology to teach a variety of skills to students with ASD and found the technology a promising line of research. Two of their studies focused on teaching social skills to students with ASD and reported positive treatment effects in moderate to high virtual immersion (Miller & Bugnariu, 2016; Reed et al., 2011). However, a good deal of relevant information was missing in these two studies including participants' characteristics (i.e., age, IQ), treatment agents (i.e., teacher, researcher), treatment settings (i.e., clinic, school), and whether social skills taught were maintained or generalized. Howard and Gutworth (2020) meta-analyzed virtual reality training programs to teach social skills such as awareness of social space, body language, and verbal tone. Unfortunately, they did not examine the effects on participants with different disabilities and profiles. Howard and Gutworth found no significant differences between VR programs with gaming versus non-gaming elements or fully immersive versus non-immersive environments.

All of the above reviews have provided relevant information about the ability to use virtual and augmented technology for teaching purposes. However, researchers have reported gaps in the literature (Bellani et al., 2011; Merchant et al., 2014; Miller & Bugnariu, 2016; Sansosti et al., 2015) particularly in participant attributes and skills selected for instruction. Extant literature has yet to explore these studies taking into consideration the treatment agents, targeted social skills, program goals, and interventions used within the environment. Therefore, a systematic review is necessary to explore and understand both the acceptability and usefulness of virtual technologies as well as the ability of the intervention to promote social skill acquisition, generalization, and maintenance for students with ASD.

Research Purpose and Questions

To better understand the use of innovative technologies to teach social skills to students with ASD, a review of the research is needed to answer the following questions:

RQ1. Who were the participants and intervention agents in studies that used AR, VR, MR, and XR for social skill acquisition?

RQ2. What social skills were taught to students with ASD in studies that used AR, VR, MR, and XR and what skills were acquired?

RQ3. Were the social skills taught within these technologies to students with ASD generalized and maintained?

Methods

Search Procedures

A systematic search was conducted using PRISMA-P protocol and traditional approaches to identify all relevant articles (Gersten et al., 2005; Horner et al., 2005). The following databases were selected for analysis: Education Resources Information Center (ERIC), PsycINFO, ScienceDirect, and Web of Science. The search was conducted in January of 2020 and limited to articles published within the last 20 years (2000–2020) to ensure the inclusion of current technology. The following search terms were used: "autis*," and "social," and "student," and "generaliz*" and either "virtual" or "reality" to encompass all of the following: virtual environment, virtual learning, virtual reality, immersive virtual, augmented reality, mixed reality, and extended reality. The search was filtered by language (English) and limited to peer-reviewed articles. After author discussion, peer-reviewed sources were not limited to published journal manuscripts. Conference, workshop, and lecture proceedings were included for review as long as the literature underwent a peer-review process. We expanded the inclusionary criteria due to a large amount of literature available from alternative sources that may not appear in academic databases. Peer review was required to deem studies had a level of quality and a sufficient amount of scientific rigor. The initial search conducted by the first author returned 2774 articles.

To establish search reliability, the second author independently replicated the search protocol and identified a nearly identical number of articles. The first author found 2773 articles whereas author two found 2774 articles 2 days later. This slight differential in articles may be due to an article being published in the 2 days. Following the removal of the 1824 duplicate articles, a total of 950 articles were exported and combined into a single database for screening. A comprehensive hand search of five journals, two chosen for their extensive publishing of technology in special education (*Journal of Special Education Technology* and *Computers and Education*) and three chosen for their autism research (*Journal of Autism and Developmental Disorders*, *Autism Research*, and *Focus on Autism and Other Developmental Disabilities)*, resulted in one additional article. Finally, an ancestral review of the 19 available literature reviews on virtual reality and social skills was performed resulting in four additional articles for screening. Overall, a total of 955 articles were identified for screening.

Screening Procedures and Inclusion Criteria

All authors screened title and abstracts of search results and excluded all articles that did not utilize a research design (e.g., editorials, explanatory chapters, manuals, reviews). Furthermore, articles were excluded if the titles and abstracts did not utilize a social skill intervention implemented through technology with school-age children with ASD. We retained articles when title and abstracts provided insufficient information for exclusion. Authors one and three performed a title and abstract screening. The two authors disagreed on two articles resulting in a reliability of 97%. Following a discussion, a consensus was made to eliminate 884 articles and include 71 articles.

The 71 articles underwent a full review for inclusion. Articles were included if (1) virtual reality, virtual environment, augmented reality, mixed reality, or extended reality was reported as the independent variable; (2) at least one participant was reported or described to have a diagnosis of ASD; (3) occurred in an educational setting; (4) authors reported intervention impact, generalization, or maintenance; and (5) studies were empirically based using single subject, qualitative, quantitative, or mixed methods. Articles were excluded that (1) had only students younger than age 4 or only students older than age 18; (2) utilized primarily non-educational environments; (3) examined elements of virtual or reality (e.g., usability) without application of the technology for teaching or learning; (4) were not peer-reviewed (i.e., commentaries, letters to the editor, opinion articles, lectures), and (5) descriptive case studies with no reported research design or participant outcome. Peer review was a requirement for three reasons. First, research from other sources was primarily conducted by authors connected to a specific product in which the literature may have exaggerated the effects. Second, a large amount of research from alternative sources does not appear in academic databases, making it hard to ensure sources are not overlooked. Finally, studies needed to have a level of assurance that the research was deemed quality research with sufficient scientific rigor.

Following inclusionary and exclusionary review of 71 articles, 40 articles were retained. A second ancestral review was conducted using the final 40 articles which resulted in the addition of one article for a total of 41 articles. Authors one and two independently reviewed all 71 articles for reliability of inclusion and exclusion. Agreement of inclusion and exclusion by the independent review was 100% to eliminate 31 articles and add one from the ancestral review. A total of 41 articles were added to a single database for coding.

Coding Procedures

The coding database created contained 126 fields including primary and secondary quality indicators by type of experimental design (Reichow, 2011) and the quality indicators of systematic reviews in behavioral disorders (Maggin et al., 2017). Reichow included (a) participant characteristics, (b) independent variable, (c) comparison condition and dependent variable, (d) research question and data analysis, (e) visual analysis or statistical analysis, (f) experimental control, (g) random assignment, (h) fidelity, (i) attrition, (j) generalization, (k) maintenance, and (l) social validity. Maggin included (a) reported reliability, (b) research design, (c) variables under study, and (d) methodological quality. The first author coded all 41 articles independently. To establish coding reliability, article references were randomly assigned to authors two and three for coding. Coding training included reviewing the coding criteria, coding three articles, and discussing coding and disagreements until 100% agreement was achieved.

The generalization setting and the person reporting generalization were coded separately from the setting of the intervention and treatment agent. Maintenance was coded both by agent reporting maintenance and length of maintenance. The specific social skill was coded as well as whether a single social skill, multiple social skills, or social skills and other skills (i.e., academic, motor coordination) were implemented through the technology. Relationship skills included verbal and non-verbal communication, social engagement, and relationship building. Emotion recognition involved the ability to see the face of a person, character, or avatar and match it with the correct name of the emotion. Executive functioning involved the ability to focus on a task, create a plan of action, complete multiple tasks at one time, or any combination of the three. Social awareness involved understanding the causes of events or behaviors, perspective-taking, and respecting others.

It is important to note that we coded methodological quality for statistical improvement, reports of significant improvement by all key stakeholders, and by the presence of necessary information to determine validity and reliability information. We utilized the definitions of each of these by experimental design referencing Campbell and Stanley (2015) for experimental and quasi-experimental designs and Ledford and Gast (2014) for single-case research. The type of instruction within the intervention was coded as either direct instruction or observational learning. Direct instruction was coded when the program provided explicit teaching of a targeted skill. Observational learning was defined as learning from the observation of others or by a natural consequence for a given behavior (Plavnick & Hume, 2014). Additionally, we coded for each type of technology as well as whether outside measures (i.e., prompting, token reinforcement) were used.

Interrater reliability was calculated using the Cochrane Review model (Higgins & Green, 2011) in which agreement is assessed on important data criteria. For the purposes of this review and coding, important data criteria identified were established as participant attributes, environmental attributes, intervention description, treatment agent, data collection, duration of study, assessments utilized, validity and reliability reports, generalization, maintenance, and length of follow-up. Accordingly, 52 items of the 126 coding categories were evaluated, resulting in 2184 total items. Interrater reliability of the included items was calculated by percentage of agreement. Total agreements were divided by agreements plus disagreements then multiplied by 100 for each response on the coding form to calculate percentage of agreement. Interrater reliability for the 41 articles was calculated at 96.7%. A fourth outside researcher trained in the coding protocol resolved disagreements. The fourth reviewer independently coded articles where the reviewers disagreed. This information was provided to the original reviewers and then discussed as a team until consensus of 100% was reached for the 41 articles.

Results

RQ1 Participant Characteristics and Intervention Agents

A total of 524 males and 87 females received social skill intervention across the 41 experimental, quasi-experimental, and single case studies. The minimum number of participants in a study was two and the maximum was 94 participants. The ages of participants ranged from 2 to 20 years old but were primarily 8 to 13 years old. The majority of studies (n = 25, 61%) included participants with different ages. Eight studies (20%) included only elementary students, four studies (10%) included only middle school students, and two studies (5%) included only secondary students.

Co-existing diagnoses were reported for 14 (34%) of the 41 studies, with ADHD being the most common (13%). One study (Didehbani et al., 2016) compared a group of 17 participants with ASD to a group of 13 participants with ASD and ADHD and found improvements across both groups. The co-existing disabilities did not influence the intervention except in two studies (Ke & Im, 2013; Lan et al., 2018). In these two studies, participants with co-existing diagnoses had lower performance but also differed in intelligence quotients (IQs). Of the studies reporting IQs (n = 23, 56%), 18 studies (78%) reported participants having an IQ higher than 70, and 5 studies (22%) reported participants with IQs less than 70. Participant performance IQ, verbal IQ, and full IQ ranged from 49 to 125.

All 41 studies stated the specific technology used to implement the social skill. Five studies (12%) used AR, 26 (63%) used NI VR, and 10 (24%) used immersive VR. XR and MR were not used in any study. Twelve studies (29%) included additional techniques from the treatment agent beyond the technology (i.e., prompting, guidance in VR from researchers). Of the 34 studies (83%) reporting the treatment agent and setting, 19 (56%) were in schools, 10 (29%) were in a clinic, and 5 (15%) were in multiple settings (i.e., school, home, and community or school and clinic). In 14 of the 34 studies (41%) multiple treatment agents (i.e., parent and teacher) implemented the intervention, resulting in the following numbers equaling over 100%. Of the studies reporting treatment agents, 21 studies (62%) were conducted by researchers. Teachers implemented the intervention in 16 studies (47%), and nine studies (12%) were run by clinicians (i.e., speech therapist). Parents implemented the intervention in three studies (9%), and one study (3%) involved implementation by a peer. Table 1 provides a breakdown of the characteristics of each study's participants, intervention and generalization settings, technology type, immersion level, intervention duration, and targeted social skill areas.

RQ2 Social Skills Taught and Acquired

Nearly 75% of researchers (N = 30) implemented an intervention to improve multiple social skills, 17% (N = 7) taught a single social skill, and 10% (N = 4) did not clearly state the targeted skill for intervention. The primary targeted skill in studies was relationship skills (N = 21; 51%) which included interventions on verbal and non-verbal communication, social engagement, and relationship building. Studies were coded in this category if the dependent variable was the exchanging of information, whether verbally (e.g., take turns in conversation) or non-verbally (e.g., make eye contact when talking) as well as attention toward peers and motivation in engaging with peers (Gresham & Elliott, 2008; Martin, 2019). Emotion recognition was also frequently targeted (N = 14; 34%) which included the ability to see and name an emotion. Studies were coded in this category if the dependent variable was seeing an image or character and naming an emotion (e.g., happy, sad, angry). The additional skills included social awareness (N = 8; 20%), cooperation (N = 6; 15%), and executive functioning (N = 4; 10%). Studies were coded in the social awareness category if the dependent variable involved understanding the causes of events or behaviors and perspective-taking. Studies were coded in cooperation when the dependent variable included working with others to complete a task (Shih et al., 2014) and as executive functioning when the dependent variable was the ability to focus on a task, create a plan of action, complete multiple tasks at one time, or any combination of the three. The dependent variable in 30 studies (75%) included multiple targeted social skill areas (i.e., relationship skills and emotion recognition were dependent variables) which accounts for the total of all targeted skill areas being over 41.

The intervention caused statistical improvement in 15 of the 41 studies (37%). There was statistical improvement in four of the five studies implemented through AR (80%) and half of the studied implemented through immersive VR. Of the other half of the studies implemented through immersive VR, three (25%) showed mixed results and three (25%) had no statistical improvement. Only six of the 26 studies using non-immersive VR (23%) reported statistical improvement. Practitioners, parents, and researchers reported significant improvement of social skills in 32 studies (83%). The primary measures to determine social skill improvement in the studies were observation by treatment agent (85%) as well as rating scales with interviews (74%). Norm-referenced assessments were only used in 15 studies (37%) to determine intervention impact.

RQ3 Social Skill Generalization and Maintenance

Researchers in 20 studies (49%) reported whether generalization of the social skill occurred. Fifteen of these twenty studies (79%) reported students could generalize skills learned within the technology into real-world environments. Three studies (16%) reported some students were able to generalize, some were not, and one (5%) stated there was no generalization. For example, Cheng et al. (2010) used non-immersive VR to improve three students with ASD's emotion recognition and empathy and found an improvement within and outside the technology. In another display of generalization, Lee et al. (2018) found successful transfer of greeting skills learned through AR from all three students in the school, home, and community.

The maintenance of the skill(s) after the intervention was reported by 13 studies (32%), with 11 studies (85%) reporting maintenance, one study (8%) showing maintenance only for two of the three participants, and one study (8%) reporting no maintenance. For example, Lorenzo et al. (2016) found that students in the desktop environment obtained higher

Table 1 Study characteristics

Reference	Number of participants and gender	Participant characteristics and age	Intervention setting (IS) and generalization setting (GS)	Immersion level	Technology used	Number of skill areas taught	Targeted skill areas	Intervention duration	Number of sessions	Duration of session minutes
Adjorlu et al. (2017)	N: 5 5 M, 0 F	ASD Age 9–11	IS: school GS: school	VR immersive	HMD & Motion Controllers	2	Cooperation and sharing	14 days	3	15
Alcorn et al. (2011)	N: 32 29 M, 3 F	ASD Age 5–14	IS: unclear GS: N/R	VR non-immersive	ECHOES Virtual Environment on TV	U	Cooperation, helping a virtual character accurately	1 day	1	10–30
Bekele et al. (2014)	N: 20 16 M, 4 F	10 HF ASD, 10 TD Age 13–17	IS: clinic GS: N/R	VR non-immersive	Desktop Eye Tracker & Tobii X120	4	Emotion recognition, turn taking, and gaze patterns	1 day	1	60
Bernardini et al. (2014)	N: 29 28 M, 1 F	ASD Age 4–14	IS: school GS: school	VR non-immersive	ECHOES LCD Display & Eye-Gaze Tracking	3	Social initiation, gaze patterns, and relationship skills	6 weeks	Varied	15
Cai et al. (2013)	N: 15 13 M, 2 F	ASD IQ: 67–110 Age 6–17	IS: clinic GS: N/R	VR immersive	A spherical 3-D Screen, 5 Projectors, & Microsoft Kinect Gesture Recognition	5	Non-verbal relationship skills, hand gestures, interacting, and joint attention	1 day	1	60
Chen et al. (2015)	N 3 2 M, 1 F	ASD IQ: 85–101 Age 10–13	IS: school GS: school and community	AR	Intel Core i7 Computer LCD & Web Camera	2	Facial expressions and emotion recognition	2 months	18	60
Chen and Lin (2016)	N: 6 5 M, 1 F	ASD IQ: 94–113 Age 11–13	IS: clinic GS: home and community	AR	Windows 8 Tablet Camera & Storybook with Embedded AR Markers	2	Facial expressions and emotion recognition	1 month	8	35–40
Cheng et al. (2010)	N: 3 3 M, 0 F	ASD IQ: 96–120 Age 8–10	IS: school GS: home, school, and community	VR non-immersive	Laptop 3D Collaborative Virtual Learning Environment Empathy Systems	4	Emotion recognition, listening, eye contact, and empathy	3 weeks	6	30–40
Cheng et al. (2015)	N: 3 3 M, 0 F	ASD IQ: 80–84 Age 10–13	IS: school GS: N/R	VR-immersive	HMD Model I-Glasses, PC, 3D Pro, & Laptop with 3D Sketch Up	2	Social awareness and social skills	6 weeks	5	30–40
Cheng and Ye (2009)	N: 3 2 M, 1 F	ASD IQ: 91–120 Age 7–8	IS: school GS: school and home	VR non-immersive	3D Environment & Text-Based Communication System	3	Social compétence, relationship skills, and engagement	5 days	3	40
Didehbani et al. (2016)	N:30 26 M, 4 F	17 ASD, 13 ASD and ADHD IQ: 111–115 Age 7–16	IS: clinic GS: N/R	VR non-immersive	VR Second Life on Computer with Mouse	3	Social awareness, executive functioning, and emotion recognition	5 weeks	10	60
Grynszpan et al. (2008)	N: 20 18 M, 2 F	10 ASD, 10 TD IQ: 80.5 Mean Age 9–13	IS: school GS: N/R	VR non-immersive	Computer Screen Presenting Avatars	1	Emotion recognition	13 weeks	13	28–74
Halabi et al. (2017)	N: 10 N/R	10 ASD, 10 TD IQ: 80.5 Mean Age 4–12	IS: school GS: N/R	VR immersive and VR non-immersive	CAVE, Polarized Glasses with Tracking, Oculus Rift HMD, & LCD Computer	3	Relationship skills, awareness of technology impact, and satisfaction with immersion levels	2 days	2	20
Herrera et al. (2008)	N: 2 2 M, 0 F	ASD IQ: 89 Age 8–15	IS: clinic GS: school, home, community, and clinic	VR non-immersive	Virtual Supermarket on Touch Screen, with Progressive Exercises	U	Cooperation, symbolism, imagination, and pretend play	3 weeks	28	20
Ip et al. (2016)	N:52 N/R	ASD IQ: >70 Age 6–11	IS: school GS: N/R	VR immersive	CAVE with Head Position & Orientation Tracking	5	Self-regulation, social-emotional reciprocity, affective expression, and emotion recognition	2 weeks	28	60
	N: 94 86 M, 8 F	ASD IQ: > 70 Age 6–12	IS: school to clinic GS: N/R	VR immersive		3		14 weeks	28	40

Table 1 (continued)

Reference	Number of participants and gender	Participant characteristics and age	Intervention setting (IS) and generalization setting (GS)	Immersion level	Technology used	Number of skill areas taught	Targeted skill areas	Intervention duration	Number of sessions	Duration of session minutes
Ip et al. (2018)					4 Screens, Half-CAVE VR, & Middle VR for DVR- Training		Self-regulation, social-emotional reciprocity, and emotion recognition			
Jarrold et al. (2013)	N: 91 N/R	37 HF ASD, 54 TD Matched IQs: > 71 Mean IQ: 104–114 Age 8–16	IS: clinic GS: N/R	VR immersive	eMagin Z800 3DVisorHMD & 2 1.8-inch Monitors	2	Social attention and relationship skills	N/R	2	150
Ke and Im (2013)	N: 4 2 M, 2 F	3 Asperger, 1 Asperger and ADHD Age 9–11	IS: school, home, offices GS: N/R	VR non-immersive	VR-Based Second Life	3	Turn taking, interactions, and relationship skills	2–4 weeks	6–9	60
Ke and Lee (2015)	N: 3 1 M, 2 F	2 HF ASD, 1 TD Age 8–10	IS: school and home GS: N/R	VR non-immersive	OpenSim 3D Application on Local Server	5	Flexibility, identity, design, cooperation, and norm construction	5 weeks	8–12	90
Kim et al. (2015)	N: 42 29 M, 13 F	19 HF ASD, 23 TD IQ: 80–117 Age 8–16	IS: unclear GS: N/R	VR non-immersive	Pentium PC, Direct X 3D Accelerator LCD Monitor, & Joystick	2	Emotion recognition and movement toward avatar	N/R	48	N/R
Lan et al. (2018)	N: 4 3 M, 1 F	1 ASD, 2 ADHD, 1 mild MR IQ: 57–95 Age 8–9	IS: school GS: school and home	VR non-immersive	VR-Based Second Life	U	Linguistic relationship skills, usefulness of and preference toward VR	7 months	N/R	N/R
Lee et al. (2018)	N: 3 2 M, 1 F	ASD IQ: 88–96 Age 8–9	IS: school GS: school, home, and community	AR	Tablet & Large TV Monitor	1	Relationship skills (greeting specific)	6 weeks	10	50–55
Lorenzo et al. (2019)	N: 11 10 M, 1 F	6 ASD, 5 ASD Control Age 2–6	IS: clinic GS: N/R	AR	Quiver Vision App & Android Phone	2	Relationship skills and flexibility	20 weeks	40	15
Lorenzo et al. (2016)	N: 40 29 M, 11 F	20 ASD, 20 ASD Control Age 7–12	IS: clinic and school GS: school	VR immersive and VR non-immersive	Immersive VR System (IVRS) vs. Desktop VR	3	Self-control, empathy, and emotion recognition	10 months	40	35
Lorenzo et al. (2013)	N: 20 16 M, 4 F	ASD Age: 8–15 (10 age 8–11 primary and 10 age 12–15 secondary)	IS: school GS: school	VR immersive	HMD with half-CAVE	3	Relationship skills, self-control, and executive functioning	4 months	80	25
Mantziou et al. (2015)	N: 2 2 M, 0 F	1 LF ASD, 1 HF ASD Age 9	IS: school GS: school	VR non-immersive	VR Human Controlled Avatar vs. Conventional Videos & Teacher	1	emotion recognition	N/R	4	N/R
Mitchell et al. (2007)	N: 7 4 M, 3 F	ASD IQ: 65–110 Age 14–16	IS: school GS: none	VR non-immersive	VE on Desktop Monitor with Mouse	2	Social awareness and attending (in social situations in a café and on a bus)	6 weeks	3	N/R
Modugumudi et al. (2013)	N: 20 19 M, 1 F	10 autism, 10 TD Age 7–19	IS: unclear GS: N/R	VR non-immersive	CVE BioTrace on Computer	1	Emotion recognition	6 months	80	80–140
Moore et al. (2005)	N: 34 29 M, 5 F	ASD Age 7–16	IS: home GS: N/R	VR non-immersive	Desktop Monitor with Mouse	1	Emotion recognition for context and stating context for emotion	N/R	N/R	N/R
Parsons (2015)	N: 14 N/R	6 ASD, 8 TD IQ: 96–115 Mean	IS: school GS: N/R	VR non-immersive	Collaborative Virtual Learning Environment	4		2 weeks	3	30

Table 1 (continued)

Reference	Number of participants and gender	Participant characteristics and age	Intervention setting (IS) and generalization setting (GS)	Immersion level	Technology used	Number of skill areas taught	Targeted skill areas	Intervention duration	Number of sessions	Duration of session minutes
		Age 7–13					Cooperation, reciprocity, relationship skills, and engagement			
Parsons et al. (2006)	N: 2 2 M, 0 F	ASD IQ: 70–100 in PIQ, VIQ, and full IQ Age 14 and 17	IS: school GS: home, school, and community	VR non-immersive	VE on Laptop with USB Joystick and Standard Mouse	1	Relationship skills	3 months	7	30–60
Parsons et al. (2004)	N: 36 30 M, 6 F	12 ASD, 12 TD UPMPIQ 12 UPMVIQ, IQ: 55–125 Age 13–18	IS: clinic GS: N/R	VR non-immersive	VE Superscape & VR Toolkit Displayed on Computer with USB Joystick & Mouse	5	Personal space, task completion, relationship skills, money skills, and executive functioning	N/R	4–5	42–65
Saadatzi et al. (2018)	N: 3 3 M, 0 F	IQ for 1 LF ASD: 49 PIQ, 75 VIQ Full IQ for 1 HF ASD: 107 Age 6–8	IS: clinic GS: home and school	VR non-immersive	Computer, Virtual Teacher, & Small Robot Peer	4	Relationship skills, greeting, imitation, and vocabulary	4 months	1–2	N/R
Schmidt et al. (2011)	N: 4 N/R	ASD Age 11–14	IS: clinic GS: home and school	VR non-immersive	VR-Based iSocial	3	Reciprocal interactions, social awareness, and relationship skills	2 weeks	4	60
Self et al. (2007)	N: 8 6 M, 2 F	4 ASD, 4 ASD Control Age 6–12	IS: school GS: school	VR non-immersive	Low-Tech VR via Laptop vs. IVTM	3	Social awareness, time on task, and safety	5 weeks	10	30
Stichter et al. (2014)	N: 11 11 M, 0 F	ASD IQ: >75 Age 11–14	IS: school and home GS: school, home, and community	VR non-immersive	VR-Based iSocial	5	Relationship skills, motivation, social awareness, executive functioning, and cooperation	10 weeks	10	31–45
Taryadi and Kurniawan (2018)	N: 12 N/R	ASD Age N/R	IS: school GS: N/R	AR	PECS on Android Tablet	U	Relationship skills	N/R	N/R	N/R
Tsiopela and Jimoyiannis (2014)	N: 6 5 M, 1 F	LF ASD and HF ASD Age 15–20	IS: school GS: school and home	VR non-immersive	Pre-Vocational Skills Lab (PVSL) Online Game on Computer	5	Relationship skills, pre-vocational skills, stress level, self-confidence, and social awareness	2 months	4–5	45
Wang et al. (2016)	N: 11 11 M, 0 F	ASD IQ: >75 Age 11–14	IS: school GS: N/R	VR non-immersive	VR-Based iSocial & Teacher Screen Flow	3	Relationship skills, engagement, and proximity of self to other	1 day	5	N/R
Wang et al. (2018)	N: 11 11 M, 0 F	ASD IQ: >75 Age 11–14	IS: school GS: N/R	VR non-immersive	VR-Based iSocial	2	Relationship skills and embodied social presence	10 weeks	20	45
Yuan & Ip et al. (2018)	N: 72 64 M, 8 F	ASD Age: 8–9 means	IS: clinic GS: school. home, and community	VR immersive	Four-Sided CAVE with VR Goggles	5	Regulation, social awareness, relationship skills, affective expression, and emotion recognition	N/R	3	60

Note. *N/R*, not reported in study; *N*, total number of participants; *M*, male; *F*, female; *U*, unclear; *ADHD*, attention deficit hyperactivity disorder; *LF*, low functioning; *HF*, high functioning; *TD*, typically developing; *UPMVIQ/ UPMPIQ*, unidentified-diagnosis participant matched; *VIQ*, verbal IQ; *PIQ*, performance IQ frequencies of adequate behaviors in the initial sessions but students in the immersive environments displayed significantly more appropriate emotional behaviors in the real school environment which were still present 2 years following the intervention. Chen et al. (2015) found after implementing an AR intervention that all 6 children significantly ($p < .05$) and dramatically (range: 93.57–98.57%) improved in appropriate recognition and response naming of emotions during the intervention phase and remained significantly higher than at baseline (range: 86.66–94.28%) 2 weeks after the intervention. Table 2 is separated by technology type (1. AR, 2. immersive VR, and 3. non-immersive VR) and provides a detailed look at the intervention's effectiveness in improving targeted skills. The table includes the social skill's statistical improvements after the intervention as well as reported significant improvements (i.e., targeted skills improved but either did not reach statistical improvement or statistical improvement was not mentioned) after intervention. Skill generalization to additional settings and maintenance over time are listed. Table 2 also reports a yes in column four when the minimum requirements to determine study validity and reliability by design type were included and no if these requirements were not present (Campbell & Stanley, 2015; Ledford & Gast, 2014).

Discussion

The purpose of this study was to examine the research on utilizing AR, VR, MR, and XR to teach social skills to school-age children with ASD. We examined the characteristics of participants and treatment agents, the assessments used to measure growth, the social skills selected within each study, the immersive technology chosen, and the intervention method utilized within this technology.

RQ1 Participant Characteristics and Intervention Agents

Concerning our first research question, we discovered participant age did not appear to influence intervention success. For example, Lorenzo et al. (2013) compared skill instruction within a fully immersive head-mounted display with a half Cave Automatic Virtual Environment for 20 participants in two separate age groups (8 to 11 years old and 12 to 15 years old). They found both primary and secondary students carried out the social tasks with acceptable results especially in less-structured VR environments (i.e., playground). Overall, the various forms of immersive technology were just as effective for younger students as they were for older students.

The ASD severity and IQ scores varied among participants. Contrary to previous findings (Radu, 2014) which reported students with high IQs having less success with technology-delivered interventions, researchers reported high achieving students having equal, and in some cases, better benefits than those with IQs less than 70. Students with the lowest IQs in three studies were the students who showed limited acceptance of the technology and less improvement within AR and VR. For example, Parsons et al. (2004) found a significant relationship between IQ and the amount of time taken to complete a task in the VR. Individuals with higher IQs took less time to complete tasks. Parsons (2015) showed that participants with ASD who had lower verbal and executive abilities were more exploratory in the virtual environment and less task focused. Cai et al. (2013) found the three participants who were able to learn and function with minimal supervision in the VR all had IQs between 95 and 110, and the four participants who were unable to use the VR all had IQs in the 60s. This trend also existed in levels of severity within ASD. Mantziou et al. (2015) found the technology useful for the student identified as high functioning and not useful for the student identified as low functioning. In order to understand this phenomenon, future researchers must consider the training in technology use required prior to delivering the intervention. For example, a student with a lower IQ may require more time to become accustomed to the dual requirements (i.e., using controls to turn and look at the avatar speaking while listening) of the technology prior to the start of the intervention. Training time and familiarity with the technology was rarely documented within studies but would provide needed information in how participant characteristics (i.e., understanding of task requirement, prior knowledge, and familiarity with technology) influence skill acquisition.

The autism-related symptoms, sensory thresholds, and social skill and performance deficits were rarely reported in studies. When reported, researchers did not differentiate outcomes. Studies primarily reported student IQs, which are not necessarily the best indicator of ability to learn or generalize a skill. For example, a student with a low IQ may have the ability to maintain eye contact and refrain from interrupting, two pre-requisite skills for maintaining a conversation and staying on topic, whereas a student with a high IQ may not have received that specific skill instruction and therefore would be less likely to be successful on the targeted skill. A better indicator than IQ would be valid and reliable scales determining if the child was displaying a social skill deficit versus a performance deficit and if pre-requisite skills are present. A skill deficit means a particular social skill has not been taught, learned, or both. For example, a student may not know how or why they need to stay on topic when in a conversation. A performance deficit, on the other hand, is when the student understands the skill necessary to perform the task but does not apply the knowledge either in a specific environment or consistently. For example, a child may understand how to stay on topic but in conversation with peers continually switches topics. Understanding this information as well as sensory thresholds would better determine if the correlation in these studies was truly related to IQ or whether it was due to sensory avoidance and skill or performance deficits.

Table 2 Study findings by technology type 1. augmented reality, 2. immersive virtual reality, and 3. non-immersive virtual reality

Reference	Statistical Improvement	Reported Improvement	Validity & *Reliability*	Dependent Variable	Treatment Agent	Instructional Method	Results and Outcomes	Generalization	Maintenance
Chen et al. (2015)	Yes	Yes	Yes *Yes*	Observed Recognition & Response Naming of Emotions	Clinician	Direct Instruction & Observational Learning	AR caused a statistical difference in the ability to identify the 6 core emotions for all participants. The AR improved the appropriate recognition and response naming of emotions. In addition, the mean difference in performance level between the baseline and follow-up phases was significant ($p < .05$).	Yes	Yes 2 Weeks
Chen et al. (2016)	Yes	Yes	Yes *Yes*	Researcher Developed Assessment, Parent Interviews, Questionnaires	Clinician	Direct Instruction & Observational Learning	Results showed the intervention effectively attracted and maintained the attention of children with ASD to nonverbal social cues and helped them better understand facial expressions and emotions of the storybook characters. Students identified six core emotions significantly better.	Yes	Yes 4 Weeks
Lee et al. (2018)	Yes	Yes	Yes *Yes*	Baker's (2001) Social Story TM SST Test	Clinician	Direct Instruction & Observational Learning	AR significantly increased students' ability to recognize and understand relationships and appropriate responses to actions. The three-phase test data suggest that the AR with concept map intervention was moderately effective in teaching the target greeting responses to children with ASD.	Yes	Yes 28 Days
Lorenzo et al. (2019)	No	Mixed	No *Yes*	Autistic Spectrum Inventory & Questionnaire	Clinician	Observational Learning	The results do not show statically significant differences between the group with the therapist and the group with the AR App. Slight improvements appear in some items (i.e., flexibility, imitation, focus, and motivation).	N/R	N/R
Taryadi & Kurniawan (2018)	Yes	Mixed	No *Yes*	Observation	Teacher & Researcher	Direct Instruction	There was a significant improvement in communication ability after AR in all but 1 student. The increase achieved an average of 76% of the communication skills of children before treatment. The average ability level in communication before and after treatment was 47% and during the treatment was 65%.	N/R	N/R
Adjorlu et al. (2018)	No	Mixed	Yes *No*	Teacher Questionnaire, Interviews, & Observation	Teacher	Direct Instruction & Observational Learning	Improvements in turn taking, sharing, & understanding of an event with proper response. Virtual classroom that was designed similar to the real classroom was distracting. All enjoyed VR & found it easy to use. There was a total of 18 positive comments and eight negative comments on VR.	Mixed	N/R
Cai et al. (2013)	No	Mixed	No *No*	TONI-3, Parent GARS, & Observation	Clinician	Observational Learning	Nonverbal communication was inconclusive. Three participants were able to learn with minimal supervision. Three participants were able to learn but required prompting. Five participants were overwhelmed by the VR & needed mediation. Four participants were unable to use the VR.	N/R	N/R
Cheng et al (2015)	Yes	Yes	Yes *Yes*	Social Events Card Scale and Social Behaviors Scale	Researcher, Observer, & Teacher	Direct Instruction & Observational Learning	Participants improved in theory of mind & socially appropriate behavior. This improvement continued through maintenance. The VR system was shown to have the ability to present an effective learning environment for the promotion of social understanding.	N/R	Yes 20 Days
Halabi et al. (2017)	Yes	Yes	No *No*	Satisfaction of Immersion, Interview, & Impact Questionnaire	Researcher	Direct Instruction & Observational Learning	Researchers reported all systems effective for improving the communication skills of students with autism. Impact of technology on all the participants was positive. Most participants reported learning to introduce themselves when speaking to a new friend for the first time. Satisfaction for CAVE was 82-85%, for HMD was 78-82%, & for the Desktop was 57-60%.	N/R	N/R
Ip et al. (2016)	Mixed	Yes	No *No*	FT, ET, PEP-3, SAT, ABAS-II, SCAS-P, SCAC-C, & CCC-2	Unclear	Direct Instruction & Observational Learning	VR enhanced social and emotional skills. Noted improvement in self-regulation, emotional expression, and social-emotional reciprocity. There was a significant difference in the PEP-3 scores, Eyes Test, social reciprocity, and affective expression test. There was no significant difference in the Faces Test.	N/R	N/R
Ip et al. (2018)	Mixed	Yes	No *No*	FT, ET, ABAS-II, PEP-3, RPM, & CAST	Unclear	Observational Learning	Significant improvements in the project's primary measures (children's emotion expression & regulation & social-emotional reciprocity) but not in the secondary measures (emotional recognition).	N/R	N/R
Jarrold et al. (2013)	Mixed	Yes	Yes *Yes*	Social Orientation, Average Duration of Looks, & Fixation Length	Researcher	Observational Learning	Statistical improvements in social orientation, duration of looks, and fixation length. Students with ASD displayed atypical social orienting in conditions requiring them to speak while attending to avatar peers but typical social attention in condition that did not require dual tasks. These differences in attention were more pronounced with social stimuli vs. nonsocial stimuli.	N/R	N/R
Lorenzo et al. (2016)	Yes	Yes	No *No*	Frequency of Behaviors, Questionnaire, & Interviews	Teacher & Researcher	Direct Instruction & Observational Learning	This study showed a greater presence of appropriate emotional behaviors in immersive VR than the comparison desktop non-immersive VR. The immersive VR group also showed greater transfer of the acquired skills into a school environment than the non-immersive group.	Yes	Yes for 2 Years
Lorenzo et al. (2013)	Yes	Yes	Yes *Yes*	Researcher Protocol TEVISA & PIAV, Observation, & Interviews	Teacher & Researcher	Direct Instruction & Observational Learning	The visual strategies & structured and repetitive support tasks within IVE improved the acquisition of executive functioning and social skills for students. Both primary and secondary students carried out the social tasks with acceptable results, especially in less structured VR environments (ie. Playground). Both groups were able to transfer skills possibly due to teacher involvement & student motivation.	Yes	N/R
Yuan & Ip (2018)	Yes	Yes	No *No*	PEP-3 Subtests of Affective Expressions & Social Reciprocity, In Class Observation, & Communication Logs	Clinician & Researcher	Direct Instruction & Observational Learning	Students improved in affective expressions & social reciprocity, & scored higher on emotion expression, regulation, social interaction & adaptation. Statistically significant interaction between group and time on affective expressions & social reciprocity. Initially students did not want to wear goggles. Parents expressed children more proactive in greeting and communicating with neighbors & relatives, as well as being more flexible in seat & food preferences. Teachers reported students making new friends & engaging in conversations.	Yes	N/R

Table 2 (continued)

Reference	Statistical Improvement	Reported Improvement	Validity & Reliability	Dependent Variable	Treatment Agent	Instructional Method	Results and Outcomes	Generalization	Maintenance
Alcorn et al. (2011)	Mixed	Yes	No *No*	Observational Video Reaction Time	Researcher	Direct Instruction & Observational Learning	Children were able to successfully follow a virtual character's gaze and gesture cues. There was the perception by some students that the VR character was a true human being. There was a significant interaction of mutual gaze and pointing p<.01 (F=1, 30), with a strong effect size (Cohen's f= 0.477).	N/R	N/R
Bekele et al. (2014)	No	Mixed	No *No*	Expressions, Response Latency, & Confidence Ratings	Unclear	Observational Learning	Similar accuracy of facial recognition in both groups. Students with ASD showed lower confidence in their responses & substantial variation in gaze patterns. No perceptual discrimination deficits in either.	N/R	N/R
Bernardini et al. (2014)	Mixed	Yes	Yes *Yes*	Classroom Observation	Researcher	Direct Instruction & Observational Learning	Slight increase in responses between pre & posttest. Probability of responding to bids for interaction increased. 8 children increased their number of initiations to avatar, 7 produced the same number, & 4 decreased. Students found program useful, easy to use, & enjoyable.	Yes	N/R
Cheng et al. (2010)	No	Yes	Yes *No*	Empathy Rating Scale (ERS)	Researcher & Teacher	Direct Instruction & Observational Learning	The Collaborative Virtual Learning Environment system markedly improved participant performance on the ERS after the intervention and on students' ability to generalize this understanding to use empathy in their daily lives.	Yes	Mixed (2 for 60 Days)
Cheng & Jun Ye (2009)	No	Yes	Yes *Yes*	Oral Exam Scores for Social Competence	Researcher & Teacher	Observational Learning	Collaborative Virtual Learning Environment showed significant positive effects on improving participants' understanding of social competence and participants' parents reported high satisfaction. Two participants enjoyed the Collaborative Virtual Learning Environment. One was not interested in using it but gained. No statistical information was provided.	Yes	Yes 10 Days
Didehbani et al. (2016)	Mixed	Yes	No *Yes*	NEPSY-II, Triangles (Social Attribution Task)	Clinician	Direct Instruction & Observational Learning	Improved social attribution, emotion recognition, and executive functioning of analogical reasoning in all measured skills in both students with ASD and the combined ASD & ADHD group. Both subgroups were equally engaged. Not all skills reached statistical improvement.	N/R	N/R
Grynszpan et al. (2008)	Yes	Mixed	No *No*	VE Training Games within Scenarios	Researcher	Observational Learning	Students with ASD, displayed poorer performance on rich interfaces. Their learning in emotion recognition improved & transfer occurred only with non-VR, not VR. Typically developing peers made improvements after both rich (VR avatar) and simple (cartoon character) interventions.	N/R	N/R
Herrera et al. (2008)	No	Yes	Yes *Yes*	TOPP Structured & Unstructured Test of Pretend Play (ToPP), Interview, Functional Play: SPT	Researcher, Teacher, & Clinician	Observational Learning	Significant advances in performance after treatment for both children in functional, symbolic, & imagination understanding. For one child acquired skills were generalized to the external environment. In the ToPP test, memory effect occurred with the first participant in just one of the items, resulting in 1 false point in his final score. Results still suggest significant increase not statistical in scores in both participants.	Mixed	Yes 7 Weeks
Ke & Im (2013)	No	Yes	No *No*	Social Skill Questions & Interviews	Parents, Researcher, & Teacher	Direct Instruction & Observational Learning	All participants showed improved responding and interacting skills throughout intervention sessions. Most participants showed improved interactions (i.e. initiation, greeting, and conversation ending) after Second-Life intervention.	N/R	N/R
Ke & Lee (2015)	Yes	Yes	Yes *Yes*	Qualitative time-series and micro-behavior analyses.	Facilitators & a Peer	Direct Instruction & Observational Learning	Participating children demonstrated a sustained level of engagement in the collaborative design task and fulfilled the targeted design goal. The flexibility, identity, and norm construction of the two children with HFA were all higher than 75%. The communication flexibility was 56%.	N/R	N/R
Kim et al. (2015)	Mixed	Mixed	Yes *Yes*	WASI, Test for symptom-atology, cognition and emotion	Unclear	Observational Learning	Students with HFA showed significantly less tendency to use the joystick to move toward a virtual avatar expressing a positive emotion, than typically developing students. Students with HFA avoided avatars expressing negative emotions at the same rate as the control group.	N/R	N/R
Lan et al. (2018)	No	Yes	No *No*	Observation & Post-Study Interviews	Teacher & Researcher	Direct Instruction of Vocab & Observational of Social	Parents and students reported increased vocabulary knowledge, improved motivation, and increased communication and concentration. Interview of students and parents revealed the student with ASD reported liking the VR and found it easy to use. All 4 students reported similar findings of enjoying the technology and improving communication.	Yes	N/R
Mantziou et al. (2015)	No	Yes	No *No*	Facial Emotion Recognition (FER) & Observation	Teacher	Observational Learning	The ICT teaching was not significantly different than the conventional methods in terms of preference and acceptance by students. Better acceptance from the student with high functioning autism in ICT than face to face. The child with low functioning autism did not interact at all with ICT & preferred face to face interaction.	Yes	N/R
Mitchell, Parsons, & Leonard (2007)	Yes	Yes	No *No*	Interview & Observation of Social Reasoning	Teacher & Researcher	Direct Instruction & Observational Learning	Virtual Cafe led to improvements in judgments and reasoning only when assessed immediately following the VE. There was little sign of gain when testing did not directly follow VE, even when provided practice and repeated testing. There was improved ability and faster completion of successive tasks in VR. There was improved ability in 1 video on successfully choosing where to sit.	No	No
Modugumudi et al. (2013)	Yes	Yes	No *No*	Neurophysiological measures EEG & EOG	Unclear	Direct Instruction	Significant improvement in children with CVE. EG group's emotional recognition was significantly improved. 30 of the 34 students were able to understand and recognize emotions in avatars appropriately.	N/R	N/R
Moore et al. (2005)	Mixed	Yes	No *No*	Program Data & Questionnaire	Unclear	Direct Instruction & Observational Learning	30 of 34 students correctly interpreted the avatars' representation of emotions to a statistically significant level where they could recognize an emotion from an expression, select an expression to represent an emotion, & predict an expression from a simple social scenario.	N/R	N/R
Parsons (2015)	No	Yes	No *No*	Collaborative Communication & Interactions Throughout Block Challenge	Teacher & Researcher	Observational Learning	Both groups communicated similarly verbally throughout the Block Challenge. Students in the experimental group struggled with the conceptual and communicative demands of the task & needed twice the input from facilitators but did show efforts in collaboration and reciprocity. The ratio of collaborative, task-focused behaviors to task withdrawal behaviors was higher for children with ASD.	N/R	N/R

Table 2 (continued)

Reference	Statistical Improvement	Reported Improvement	Validity & Reliability	Dependent Variable	Treatment Agent	Instructional Method	Results and Outcomes	Generalization	Maintenance
Parsons, Leonard, & Mitchel (2006)	No	Yes	No *No*	Observation & Interviews on Opinions of Technology	Researcher & Participant	Observational Learning	The two participants with ASD showed a very positive response to the virtual environment and showed evidence of retaining social knowledge gained during their VE sessions three months after the sessions completed. The pairs of children with ASD made more communicative moves to their partners than the TD children, with an improvement in targeted communication as they became more familiar with the task.	Yes	Yes 91 Days
Parsons, Mitchell, & Leonard (2004)	No	Yes	No *No*	Five of the EF Subtests in BADS & Observation	Researcher & Participant	Observational Learning	Groups did not differ significantly in overall time taken to complete task. Experimental group had significant trend of improvement across trials despite impaired sense of personal space. Control group & VIQ-match showed no significant differences in task completion. Control group scored significantly lower than the PIQ-match in all subtests except card shift. VIQ match displayed inconsistent performance & no significant improvements on time taken to do tasks unlike control group.	N/R	N/R
Saadatzi et al. (2018)	No	Yes	No *Yes*	Acquisition & Vicarious Learning of Sight Words	Researcher	Observational Learning for Social (DI for Academic)	All 3 acquired, maintained, & generalized all words explicitly taught through VR and vicariously learned 94% of the words instructed only to the robot, which is consistent with human-delivered instruction. Parent & researcher stated significant improvement in social response & imitation, but no statistical improvements noted.	Yes	Yes 2 Months
Schmidt et al. (2011)	No	Yes	No *No*	Reciprocal Interactions Recorded on Video	Researcher, Peers & Online Guide	Direct Instruction & Observational Learning	Overall high levels of appropriate reciprocal interactions in Collaborative Virtual Learning Environment with variation across students & context. The dominant appropriate interaction behavior was response & dominant inappropriate interaction was interruption. That participants were able to engage in successful reciprocal interactions in the multi-user environment similar to real world interactions.	N/R	N/R
Self et al. (2007)	No	Yes	No *No*	Amount of Time It Takes to Complete Emergency Procedures	Clinician	Direct Instruction	Both VR and IVTM successfully taught how to respond appropriately during fire and tornado safety drills in school environments. However, the IVTM learning was transferred to real-world situations but the VR learning transferred to school but not the community.	Mixed	Yes 4 Weeks
Stichter et al. (2014)	Yes	Yes	Yes *Yes*	SRS, BRI, PBM-Social Competence Inventory (SCI), Intervention Rating Profile, Observations, Questionnaire Likert Scales	Teacher, Parent, & Researcher	Direct Instruction & Observational Learning	Parents and teachers reported significant improvements in relationship skills, motivation, self-advocacy, and executive functioning after iSocial. Satisfaction was 5.38 of 6 for parents & 5.1 of 6 for teachers & 2.67 of 3 for students. Generalization reported consistently by parents and students in all targeted skills but not in executive functioning. Parents' reports of students' social behaviors and interactions were significantly improved. Results of t tests indicated significant improvement in overall social responsiveness ($t = 3.72$, p\.01), particularly in the domains of social cognition, social communication and social motivation. Teachers' reports and students' scores were positive but did not obtain statistical significance on social tasks.	Yes	N/R
Tsiopela & Jimoyiannis (2014)	No	Yes	No *No*	Time to Complete Task, Accuracy, Biofeedback Recordings & Questionnaire	Teacher & Researcher	Direct Instruction & Observational Learning	Intervention had positive impact on behavioral & communication skills, & practicing and developing pre-vocational skills (e.g., organizing, sorting). Researchers reported that students showed excitement and motivation towards curricular content presented in virtual environment. Speed and accuracy in all cases improved. Positive fidelity and social validity data show significant promise for the use of iSocial and VLE.	Yes	Yes 14 Days
Wang et al. (2016)	No	Yes	No *Yes*	Embodied Social Presence (ESP) Assessment in 13 Naturalistic Activities (NA)	Teacher	Observational Learning	Students experienced ESP in 97% of activities. The NA activities in which students reported a higher sense of ESP had four features: 1) narratives, 2) choosing roles, 3) fantasy settings, and 4) ease of use of learning tools. No causal relationship of learners' achievement of ESP and 3D- Collaborative Virtual Learning Environment.	N/R	N/R
Wang et al. (2018)	Yes	Yes	No *No*	Observation of ESP & Verbal & Nonverbal Social Interactions & Interviews	Teacher & Online Guide	Observational Learning	Certain patterns of verbal and nonverbal social interactions can be fostered through avatar-mediated interactions in 3D- Collaborative Virtual Learning Environment. When verbal interactions include realistic nonverbal signals, they are more likely to achieve ESP.	N/R	N/R

N/R, not reported ins; *LFA*, low functioning autism; *HFA*, high functioning autism; *UPMVIQ/ UPMPIQ*, unidentified-diagnosis participant matched based on *VIQ*-verbal IQ *PIQ*-performance IQ; *CAST*, Childhood Autism Spectrum Test; *IVTM*, integrated video teaching model which includes video modeling, social story, maze, and role play; *PBM*, performance based measure; *PECS*, Picture Exchange Communication System; *ABAS-II*, Adaptive Behavior Assessment System 2nd Edition; *SCAS-P & SAS-C*, Spence Children's Anxiety Scale-parent version & children's version; *SAT*, Social Attribution Task; *CC-2*, Children's Communication Checklist; *FT*, Faces Test; *GARS*, Gilliam Autism; *NEPSY-II*, Developmental Neuropsychological Assessment Second Edition; *PEP-3*, Psychoeducational Profile, third edition; *SRS*, Social Responsiveness Scale; *TONI-3*, Test of Nonverbal Intelligence-Third Edition; *BADS*, Behavioral Assessment of the Dysexecutive Syndrome

The majority of treatment agents were researchers, despite the majority of interventions occurring within schools. Teachers were the sole implementation agent in only five studies and no studies were implemented by parents alone. This finding is important as the training of teachers and parents was non-existent in most studies and extremely limited in the studies which reported training. Without the involvement of the primary daily educators of these participants, the intervention is unlikely to be sustained at the same level post-treatment.

RQ2 Social Skills Taught

We found a substantial amount of studies did not report sufficient information to thoroughly answer our second research question. The social skills reported as "taught" within the studies varied greatly in the presentation of information as well as the clarity of the targeted skill. Almost 75% of researchers implemented an intervention to improve many social skills rather than a single social skill, making it hard to determine if the intervention was effective in teaching a single specified skill. Practitioners, parents, and researchers reported significant improvement of social skills in 32 studies (83%). However, observational learning alone was only effective when teaching relationship skills and cooperation, not when teaching emotion recognition, executive functioning, and social awareness. Exploring this finding further may determine if relationship skills and cooperation are able to be taught to students with ASD through observing other avatars or characters and noticing natural consequences. Emotion recognition, executive functioning, and social awareness may require direct instruction for mastery and may not be able to be assimilated from observation alone. This finding would be invaluable to educators as past research in the field has shown few social skills as being able to be mastered for students with ASD without direct instruction (Plavnick & Hume, 2014).

The intervention caused statistical improvement in 15 of the 41 studies (37%). AR had the most statistical improvement (80% of studies), followed by immersive VR (50% of studies) and non-immersive VR (23% of studies). It is important to note that the 25% of studies using immersive VR which showed no statistical significance occurred primarily due to specific participants not tolerating the sensory requirements of the HMD and goggles. It is also important to consider that only 38% of studies provided adequate information to determine the study's reliability and validity by study design. Until this number improves, it is difficult to determine the exact accuracy of reported improvements. Participants and treatment agents reported significant improvements (i.e., surveys, questionnaires, interviews) in 83% of studies (60% of studies using AR, 80% of studies using immersive VR, and 88% of studies using non-immersive VR). AR statistically appeared to have greater success, yet participants and treatment agents reported VR more consistently as successful. It will be important for future researchers to consider both the improvements in skills noted by statistical measures as well as the agreed upon improvement in skills reported by parties directly observing the newly acquired social skills.

RQ3 Social Skill Generalization and Maintenance

Approximately half of the studies (49%) reported whether generalization of the social skill occurred. Studies with reported generalization of learned skills into real-world scenarios (79%) were high. Only one study reported no generalization in any of the targeted social skills.

Maintenance of the training post-intervention was also high (85%) among the 13 studies reporting maintenance, though the lengths of the reported intervals of maintenance varied from 10 days to 2 years. Future studies should include both the ability of students to generalize targeted social skills and long-term measurement of maintenance. Instruction in social skill acquisition is only effective if these skills are able to be used in multiple settings and maintained over time. Future research should also consider whether providing systematic training in immersive technology to the student and a student's primary interventionist may over time improve the ability to establish social skill maintenance and generalization.

Limitations

The inclusion criteria allowed only peer-reviewed studies from 2000 to 2020, which used AR, VR, MR, and XR to instruct school-age children with ASD in an educational setting. Additional studies were available but were either not peer-reviewed, did not involve teaching a specific social skill, or were not implemented with school-age participants and therefore were not included. Choosing to focus on school-age students does not provide enough information to determine the implications of this research for those younger than four and adults with ASD.

A second limitation was our inclusion criteria allowed studies that taught many social skills through multiple methods within the technology. A systematic review that uses a more stringent criterion would likely produce a smaller sample of studies. Future authors may consider refining criteria to separate these variables. A third limitation was that this review was limited to specific researcher coding definitions. While we controlled for ambiguous definition through agreement from multiple coders, observational learning as well as social skill categories may be defined and evaluated differently by different researchers.

Implications for Research and Practice

Results from this review suggest AR and VR are promising technologies for providing social skill instruction to students with ASD. AR and VR were found useful by participants and treatment agents in 94% of studies reporting usefulness. In the 26 studies reporting significant improvements, researchers utilized AR and VR to target an array of social skill areas (i.e., relationship skills, emotion recognition, social awareness, cooperation, executive functioning).

Our findings that significant improvements were reported in all five social skill areas contradicts those of Howard and Gutworth (2020) who stated complex social skills were the only skills successfully taught through VR. Before a determination can be made as to what level of social skills can be effectively taught through AR and VR, the students' skill levels and deficits prior to the intervention must be reported. For example, Howard and Gutworth may have come to this conclusion because students learning simple social skills were at different skill acquisition levels prior to intervention than those learning complex social skills. Students with a larger repertoire of skills prior to intervention could make significant progress less likely than it would for students with no prior understanding of the specific skill. This finding from Howard and Gutworth may also be due to the intervention within the technology they presented being observational and not including direct instruction. Complex social skills may be more comfortably taught through observational learning and not require as much direct instruction as primary social skills.

The literature suggests AR and VR improve additional skills beyond the targeted ability. For example, Tsiopela and Jimoyiannis (2014) used a non-immersive virtual computer game to teach primarily pre-vocational skill speed, the accuracy of vocational skill (e.g., organizing, sorting), and self-confidence. Researchers reported a positive impact on communication skills, social awareness, and relationship skills, as well as the targeted confidence, speed, and accuracy of pre-vocational skills. This finding suggests that students may observe and practice within the technology skills outside of the technology's instructional objective. This finding is important because it also suggests that observational learning is taking place within the intervention that is improving non-targeted skills. Therefore, it is imperative for programmers of these interventions to ensure that all avatar or character movements and responses within the intervention are socially acceptable for the targeted population.

Future research should develop a protocol for training treatment agents to assess the role of different variables (i.e., whether agents are customizing content, monitoring student learning, using intervention-specific vocabulary in their day-to-day instruction). Either a protocol for intervention methods used within the VR or descriptions of the programmed interventions currently implemented through VR and AR would be beneficial for understanding cause and effect relationships. Sustainability may be increased by providing training in the technology to both treatment agents and participants. Providing scripts of instruction occurring within the intervention would furnish the needed information to determine the primary method of teaching within the intervention. All of these variables play a role in skill maintenance and generalization. Understanding the type of feedback would help researchers determine if students were able to feel rewarded for progressing through the scenarios or if students require rewarding aspects within the intervention (i.e., badges, trophies). Interactions and training within and outside the environment should be evaluated to determine the effect on the AR or VR delivered intervention.

There were no articles fitting our inclusion and exclusion criteria which used MR or XR to deliver social skill instruction. However, MR has been useful in other content areas at providing an intervention through which learning is generalized and maintained (Sheik-Ali et al., 2019). Based on the studies in this literature review, AR has the potential to generalize instruction better and VR has the potential for providing a practice environment for performance deficits. Combining these two technologies may provide a more cohesive intervention. Students could learn and practice skills in VR environments where the anxiety of the participant tends to lessen and motivation is high. Then, the student could transition into the real environment and use AR-developed tools similar to those used in practice. The AR would allow the tools to become interactive in the real-world environment through visual, auditory, and haptic feedback. For example, students with ASD could use the free social skill web-based VR VOISS to learn the skill. Then, an AR App on a student device when placed on specific QR codes throughout the school would pull up helpful skills for this setting learned in the VR (i.e., taking deep breaths when anxious in the classroom, starting a conversation in the hallway, dealing with the noise level in the gym). The student could watch the skill within their actual environment and imitate the skill until reaching mastery. XR would take this a step further and provide this technology with a focus on an individual's background skills, sensory experiences, and technology acceptance. Research is showing that MR and XR technologies are leading to improved academic outcomes (Ziker et al., 2021). It is worth exploring how MR and XR could benefit students with ASD as well as all students seeking to attain, generalize, and maintain targeted social skills.

Finally, providing future methodologically robust investigations in a longitudinal study will help determine causal relationships. Separating the variables of participant characteristics, treatment procedures, virtual technology employed, the interventions used within the virtual environment, and methods utilized for generalization and maintenance will improve research in this area. Currently, the forms of technology under the category "virtual technology" (i.e., immersive VR, non-immersive VR, AR, MR, XR) differ substantially. For example, the user may participate in VR as an avatar, and this varies from experiencing VR in the first person, where body movements are taken into account by the program. This would be similar to the difference between basic video modeling (i.e., participant watches video of person completing task) and point-of view modeling (i.e., participant watches video as if they are the person completing the task). More robust investigations could determine what aspects of the virtual technology are best suited for performance and skill deficits, as well as whether cultural factors influence the intervention (i.e., in certain cultures teacher-directed instruction may be more appropriate than student-directed). Until there is further evidence on using AR, VR, MR, and XR to teach social skills to students with ASD, practitioners may want to consider utilizing the technology to enhance current instruction and practice skills rather than as the sole instruction agent.

Declarations

Conflict of Interest The authors declare no competing interests.

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