Review Journal of Autism and Developmental Disorders

Virtual reality and augmented reality for children, adolescents, and adults with communication disability and neurodevelopmental disorders: A systematic review

--Manuscript Draft--

Manuscript Number:	
Full Title:	Virtual reality and augmented reality for children, adolescents, and adults with communication disability and neurodevelopmental disorders: A systematic review
Article Type:	Review Paper
Funding Information:	
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Conflict of interest: The authors declare that they have no conflict of interest.

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Abstract

This review investigated virtual reality and augmented reality (VR/AR) communication interventions for children, adolescents and adults with communication disability and neurodevelopmental disorders, as well the feasibility of these technologies. A search of five scientific databases yielded 5,385 potentially relevant records of which 69 met inclusion criteria. Studies reported on a wide range of VR/AR devices, platforms, and applications for people with autism spectrum disorder, communication disorders, and intellectual disability. Some VR/AR systems hosted effective communication interventions; however, participant outcomes varied across the included studies. Most participants with neurodevelopmental disorders and their supporters were able to access learning experiences using VR/AR and few adverse effects were reported. Directions for future research are discussed.

Key words: virtual reality; augmented reality; communication disability; neurodevelopmental disorders.

Virtual reality and augmented reality for children, adolescents, and adults with communication disability associated with neurodevelopmental disorders: A systematic review

Neurodevelopmental disorders are conditions which manifest early in life and are characterised by impairments in personal, social, academic, motor, and/or occupational functioning (American Psychiatric Association; APA, 2013). These include attention-deficit/hyperactivity disorder, autism spectrum disorder (ASD), communication disorders, global developmental delay, intellectual disability, motor disorders and specific learning disorders. Neurodevelopmental disorders are associated with a wide range of limitations in community participation and broader functioning. For the purposes of this review, we focus specifically on the neurodevelopmental disorders associated with communication disability, namely intellectual disability, global developmental delay, communication disorders, and ASD.

Communication plays a fundamental role in self-determination and contributes to quality of life outcomes for people with neurodevelopmental disorders (Chamak & Bonniau, 2016; Johnson, Beitchman, & Brownlie, 2010). Indeed, interventions designed for people with neurodevelopmental disorders often have a strong focus on improving communication skills (Rogers et al., 2012). Such programs commonly emphasise a need for intensive intervention delivered early in life (Webb, Jones, Kelly, & Dawson, 2014). However, many families and people with neurodevelopmental disorders have difficulty accessing interventions, particularly those living in rural and remote areas where geographical isolation and health workforce shortages impact service availability (Jones, McAllister, & Lyle, 2016; Vohra, Madhavan, Sambamoorthi, & St Peter, 2014). These challenges have led researchers to investigate the feasibility of telehealth models of service delivery, with preliminary findings showing that some interventions designed for face-to-face delivery may be successfully adapted and provided using telehealth (e.g., Vismara, McCormick, Young, Nadhan, & Monlux, 2013). Researchers are now beginning to turn their attention to whether other technologies, such as virtual reality and augmented reality, may be useful in the delivery of communication interventions (Bryant, Brunner, & Hemsley, 2019).

Virtual Reality and Augmented Reality

In the absence of universally accepted definitions, we use the term ‘virtual reality’ in this paper to refer to computer technologies which create a three-dimensional environment that integrates the user, allowing interaction with digital people, objects, and/or materials (Virtual Reality Society, 2017). The term ‘augmented reality’ (AR) is used for similar technologies, but rather than immersing the user in an entirely digital environment as in the case of VR, AR projects digital people, objects, and materials into the user’s real-world surroundings (Carmigniani et al., 2011). VR/AR are presented using a range of hardware, including desktop computers, which provide a non-immersive experience; or specially designed rooms with interactive projection systems (i.e., a Cave Automatic Virtual Environment or “CAVE”) or a head-mounted display (HMD), both of which provide a fully immersive experience. Immersive and non-immersive VR/AR technologies could be used to host clinical services by simulating communication intervention materials or activities, used offline or online. As such, they might be included in a suite of applications designed for use in telehealth models of service delivery, and provide useful communication interventions for children, adolescents, and adults with neurodevelopmental disorders.

Research on VR/AR is emerging across allied health disciplines involved in supporting people with neurodevelopmental disorders. Prior reviewers of the literature involving people with ASD have reported preliminary support for the safety and utility of VR/AR in improving users’ social communication skills (Bellani, Fornasari, Chittaro, & Brambilla, 2011; Irish, 2013; Parsons & Mitchell, 2002; Vasquez et al., 2015). However, some younger users with ASD have difficulty accessing these technologies (Parsons, 2005) and there is not yet sufficient evidence to support VR/AR interventions as evidence-based practices (Duffield et al., 2018; Parsons & Cobb, 2011; Parsons & Mitchell, 2002). There is also some support for the use of VR in improving the social communication skills of adults with intellectual disability (de Oliveria Malaquias & Malaquias, 2016; Standen & Brown, 2005) and providing authentic learning experiences for stuttering interventions (Brundage, 2007). As far as we are aware, none of the prior reviews have explored the research on VR/AR communication interventions for people with global developmental disorder or communication disorders other than stuttering, or across the various neurodevelopmental disorders. In addition, no prior review has compared VR/AR communication intervention outcomes across studies or provided a quality appraisal of studies in this field. These issues must be addressed if clinicians are to make evidence-based decisions regarding the clinical use of VR/AR technologies for people with neurodevelopmental disorders (APA, 2006).

Therefore, the aim of this systematic review was to investigate: (1) the effects of VR/AR interventions on the communication skills of children, adolescents and adults with communication disability associated with neurodevelopmental disorders; and (2) the feasibility of using VR/AR with children, adolescents and adults with communication disability associated with neurodevelopmental disorders, and any barriers and facilitators to the use of these technologies. The review includes a formal analysis of research quality and comparison of VR/AR intervention outcomes using standardised effect size measures.

Method

This review was registered with the PROSPERO international prospective register of systematic reviews (http://www.crd.york.ac.uk/PROSPERO, registration number: CRD 42019136635). An extensive search of the literature was undertaken to identify studies on: (i) the effects of VR/AR interventions on the communication skills of children, adolescents and adults with neurodevelopmental disorders associated with communication disability, and (ii) the feasibility of using VR/AR with this population.

Key word searches were completed using the MEDLINE, Embase, ERIC, CINAHL, and PsycINFO databases using target population terms combined with VR and AR terms. The target population was people with neurodevelopmental disorders associated with communication disability as per the Diagnostic and Statistical Manual of Mental Disorders – 5th edition (APA, 2013): intellectual disability, global developmental delay, communication disorders, and autism spectrum disorder. Population search terms included neurodevelopmental* OR developmental dis* OR developmental impair* OR developmental delay OR intellectual dis* OR intellectual impair* OR mental retard* OR global developmental delay OR language impair* OR language dis* OR speech sound dis* OR speech sound impair* OR speech dis* OR speech impair* OR fluency dis* OR fluency impair* OR stutter* OR communication dis* OR communication impair* OR voice OR social communication dis* OR pragmatic dis* OR autis* OR Asperger. VR and AR search terms were virtual* OR augmented reality OR extended reality OR mixed reality. An ancestry search was conducted for each study which met inclusion criteria. Forward citations were checked, and first author surnames were entered into the Google Scholar search engine to uncover additional relevant titles.

Inclusion Criteria

To be included in the review, studies needed to: (a) be original research, (b) be published in peer-reviewed journals, (c) be written in English, (d) include at least one participant with a neurodevelopmental disorder associated with communication disability, and (e) present findings on the feasibility or effects of VR or AR technologies on users' communication skills.

Operational definitions for VR and AR were constructed based on definitions from the Virtual Reality Society (2017) and Carmigniani et al. (2011), respectively. To be considered VR, the technology had to generate a virtual environment which was presented in 3D and enabled the user to (a) be part of the virtual world, (b) explore and interact with the environment, and (c) manipulate virtual objects. To be considered AR, technologies had to (a) permit a real-time 3D view of the physical world with added computer-generated information, and (b) enable users to interact with the virtual content in the physical world.

Data Extraction and Analysis

Data Extraction

Data from the included studies was extracted on (a) publication bibliographic details of first author and year, (b) study design, (c) method, (d) participant characteristics, (e) VR/AR characteristics, (f) VR/AR feasibility (acceptability, immersion, user experiences and perceptions, implementation barriers, and facilitators), and (g) outcomes following VR/AR intervention. Data extraction was conducted by the first author and checked by the second author. Agreement statistics were excellent ($\kappa = .964$, $p < .01$) and the authors were able to come to consensus on all instances of disagreement.

Quantitative Analysis

Quantitative findings relating to VR/AR communication intervention outcomes were analysed via two processes. For single-subject studies, WebPlot-Digitizer data extraction software (Rohatgi, 2008) was used to extract data with high reliability and validity (Moeyaert, Maggin, & Verkuilen, 2016). Graphed information was converted to numerical data for the purpose of calculating Nonoverlap of All Pairs (NAP; Parker & Vannest, 2009). This is an index of overlap used to determine improvement across adjacent experimental phases (baseline and VR/AR exposure). NAP was selected for use in the current study on account of its superior external validity, efficiency, and accuracy as compared to other overlap indices (Parker & Vannest, 2009). NAP scores of 0-0.65 represent weak effects, 0.66-0.92 medium effects, and 0.92-1.00 strong effects. For group studies, standardised mean difference effect sizes were estimated based on mean pre- and post-exposure to VR/AR scores using Hedges' *g* (Cooper & Hedges, 1994). Hedges' *g* was selected for use in this study as it is less susceptible to error when used to estimate effect magnitude in studies involving small samples which are common in research involving people with neurodevelopmental disorders (Hedges & Olkin, 1985). Guidelines for interpreting Hedges' *g* suggest that 0.2 is a small effect size, 0.5 is a medium effect size, and 0.8 is a large effect size (Cohen, 1992).

Qualitative Analysis

Qualitative findings were extracted and coded using content thematic analysis (Joffe & Yardley, 2004). The first author read and re-read the texts and created open codes to reflect the meaning of the content presented. Codes were discussed with co-authors to verify researcher interpretations. The authors discussed the content codes to reach consensus on the categories of meaning that expressed and synthesised the qualitative findings across studies. Codes were grouped into themes, and key quotes were identified to illustrate meaning within each theme. Quotes are reported within the results to provide transparency in the authors' interpretation.

Analysis of Research Quality

A quality appraisal was conducted using the Quality Assessment Tool (QATSDD; Sirriyeh, Lawton, Gardner, & Armitage, 2012). This is a 16-item scale with good validity and reliability designed to draw broad quality comparisons between quantitative, qualitative, and mixed methods research.[1] Items relate to both methodological and theoretical aspects of research and were rated using a four-point scale aided by guidance notes (see Sirriyeh et al., 2012, for complete list of scale items). Ratings derived using the QATSDD are expressed as a percentage of possible quality scores. The first author conducted the quality appraisal and each judgement was checked by the second author. There was a good level of agreement between the first and second authors ($\kappa = .859$, $p < .01$) and all disagreements on ratings were resolved through consensus discussions.

Results

Results of the search strategy are presented in Figure 1. The key word database search identified 5,344 potentially relevant studies and an additional 41 potentially relevant studies found via the ancestry search. Titles and abstracts for the 5,385 studies were screened for relevance to VR/AR and neurodevelopmental disorders associated with communication disability. After removing duplicates, 340 studies were retrieved for full text review. In total, 271 studies were excluded at full text stage on the basis of publication type (*n* =113), research design (*n* = 29), participant characteristics (*n* = 76), and type of computer technology (*n* = 53), leaving 69 studies in the review.

- Insert Figure 1 here -

Analysis of Research Quality

Research quality ratings derived using the QATSDD ranged across the included studies from 14% to 86% with a median quality rating of 56%. Studies were most frequently awarded low quality ratings on items relating to sample size, reliability of qualitative analytic processes, and reliability and validity of quantitative measures. Findings from each of the reviewed studies are considered in the following sections; however, greater emphasis is placed on higher-quality over lower-quality studies as identified based on a median split of QATSDD ratings. Table 1 and Table 4 provide an overview of study characteristics, including quality classifications, and key findings on the effects of VR/AR interventions and the feasibility, barriers and facilitators of VR/AR for people with neurodevelopmental disorders, respectively. Across both tables, studies are grouped by type of VR/AR hardware arranged in order of least to most immersive.

- Insert Table 1 here -

Effects of VR/AR Interventions

Of the included 69 studies, 29 reported on the effects of VR/AR communication interventions on children, adolescents and/or adults with neurodevelopmental disorders[2]. All but one of these studies focused specifically on people with ASD. The remaining study was an investigation of AR for individuals with intellectual disability. The reviewed interventions offered opportunities to participate in social scenarios (e.g., job interview) or practice discrete social communication and play skills (e.g., affect expression), and were presented on a range of platforms, including desktop computers, smartphones, tablets, CAVE systems, and HMDs. Table 2 and Table 3 provide an overview of the intervention outcomes achieved using each of these VR/AR platforms.

- Insert Table 2 here -

Desktop VR

VR presented on a standard computer screen, a touch computer screen, or projected computer screen (desktop VR) was the focus of 13 studies. Participants navigated these virtual environments using a keyboard and mouse, a touchscreen, or their gaze, voice, and gestures detected using eye tracking, audio, and motion sensing technologies. Intervention programs offered a variety of experiences including opportunities to participate in social scenarios, such as navigating a virtual a café (e.g., Mitchell, Parsons, & Leonard, 2007); or practice discrete social skills, such as interpreting facial expressions (e.g., Cheng & Ye, 2010). Instruction was provided within the virtual experiences through an educator- or therapist-controlled avatar and/or face-to-face in the physical world.

Effect size estimates based on two quasi-experimental studies involving the desktop VR iSocial program showed that desktop VR was moderately effective in improving general social communication skills in children and adolescents with ASD (Laffey, Stitcher, & Galven, 2014; Stitcher, Laffey, Galven, & Herzog, 2014). However, the effects of desktop VR on users' general social communication skills varied across the included studies, with effect sizes ranging from very small to very large (Laffey et al., 2014; Stitcher et al., 2014; White et al., 2016). A similar pattern of results was found among studies involving people with ASD which employed more discrete outcome measures. For example, quasi-experimental and multiple baseline studies by Cheng and Ye (2010) and Kandalaft, Didehbani, Krawczyk, Allen, and Chapman (2015) reported statistically significant gains in participants' understanding of social overtures with moderate to large effect sizes while others reported non-significant changes for the same outcome (Didehbani, Allen, Kandalaft, Krawczyk & Chapman, 2016; Stitcher et al., 2014). Mixed results were also reported in relation to post-VR instruction gains in responding and initiating social overtures (Bernardini, Porayska-Pomsta, & Smith, 2014; Ke & Im, 2013; Ke & Moon, 2018) as well as affect recognition and play skills (Cheng & Ye, 2010; Didehbani et al., 2016; Kandalaft et al., 2013; Zhao, Swanson, Weitlauf, Warren, & Sarkar, 2018). A study by Kandalaft et al. (2013), the only study to investigate conversation outcomes, found moderate gains in the conversation skills of adults with ASD who received instruction using the Second Life program (Bell, 2009).

Tablet VR

MacCormack and Freeman (2019) investigated communication intervention presented using VR on a tablet computer (n = 3) or smart phone (n = 1). In this descriptive single-subject study, four adolescents with ASD participated in face-to-face group discussion and explicit teaching of social skills, and collaborative construction activities using Minecraft.

This program enables users to construct buildings and talk with other person-controlled avatars in an expansive virtual environment. While effect size measures could not be derived from the reported data, descriptive statistics showed an increase in participants' rate of initiated social overtures as they progressed through the intervention. Furthermore, a change in the quality of participants' play during the intervention was reported, with early sessions involving mostly parallel play and later sessions involving a greater proportion of social and cooperative play.

CAVE VR

Four studies investigated CAVE VR programs (Ip et al., 2018; Jacques, Cloutier, & Bouchard, 2018; Lorenzo et al., 2013; Lorenzo, Lledó, Pomares, & Roig, 2016). CAVE VR involves participants being placed in a specially designed room where a projection system casts a virtual environment onto the walls and creates a first-person, immersive environment. In the reviewed studies, virtual experiences presented using a CAVE provided opportunities for children, adolescents, and adults with ASD to participate in social scenarios, such as sharing a lift (Ip et al., 2018; Jacques et al., 2018; Lorenzo et al., 2013; Lorenzo et al., 2016). Feedback and instruction were provided by an educator/therapist in the physical world. Participants interacted in the virtual environments by moving about the CAVE and using gestures which were captured by motion sensing technologies.

Effect size measures could be derived for one of the studies on CAVE VR (Ip et al., 2018). In this quasi-experimental study, children and adolescents with ASD took part in a range of small group social interactions using a purpose-built program. Participants also received physical-world social communication training sessions. Results showed statistically significant but relatively modest gains in users' affect expression and social-emotional reciprocity following CAVE VR instruction. No changes were observed in participants' affect recognition skills or broader communication and social functioning. Descriptive statistics reported by Jacques et al. (2018) showed improvement in a participant's understanding and response to social overtures following CAVE VR instruction. The methods used to measure outcomes in the studies by Lorenzo et al. (2013) and Lorenzo et al. (2016) were unclear and difficult to interpret.

HMD VR

A single case multiple probe design study investigated a fully immersive communication intervention presented on a HMD (Cheng, Huang, & Yang, 2015). Three adolescents with ASD participated in a range of virtual social scenarios (e.g., catching a bus) which were navigated using directional keys on a standard keyboard and by typing and/or verbally answering questions. Effect size estimates showed that participants made strong gains in their understanding and ability to initiate social overtures during the intervention, suggesting that fully immersive VR was highly effective in improving these discrete skills.

- Insert Table 3 here -

Desktop AR

Three studies investigated desktop AR interventions targeting affect recognition, shared play or job interview skills for children, adolescents and adults with ASD (Burke et al., 2018; Chen, Lee, & Lin, 2015; Chung, Vanderbilt, & Soares, 2015). A fourth study by Byrne et al. (2015) evaluated a desktop AR intervention targeting job interview skills for children, adolescents, and adults with intellectual disability. Participants interacted the desktop AR systems by performing actions in the physical world (e.g., waving) which were captured using motion-sensing technologies. Feedback and instruction were provided by educators or therapists in the physical world.

A single-case A-B-A design study by Chung et al. (2015) investigated the effects of a shared play program involving commercially available desktop AR games for children with ASD. Results showed that some participants engaged in more reciprocal social interaction as they progressed through the intervention, but effect size estimates revealed that these gains were small in magnitude. Findings from lower-quality studies involving adolescents and adults with ASD showed that desktop AR programs were highly effective in improving users' affect recognition and expression (Chen et al., 2015) and interview skills (Burke et al., 2018).

A pre-experimental study by Bryne et al. (2015) evaluated the effects of desktop AR instruction on the school participation of a large sample (N = 72) of children, adolescents and adults with intellectual disability. The Interactive Sensory Program for Affective Learning (InSPAL) AR program allowed users to participate in a range of school-based virtual scenarios (e.g., attending to classroom activities). Users reportedly achieved significant improvements in their classroom participation and behaviour during school transport, transitions, and mealtimes following instruction using InSPAL. However, while encouraging, these gains were associated with an overall small effect size.

Smartphone AR

A quasi-experimental study by Lorenzo, Gómez-Puerta, Arráez-Vera and Lorenzo-Lledó (2019) investigated the effects of AR presented on a smartphone for children with ASD. Intervention was delivered using a range of applications which provided opportunities to participate in social scenarios (e.g., shaking hands at the beginning of a game), and develop language and cognitive skills (e.g., following a therapist's instructions, imitating another's actions). Instruction outcomes were assessed using a broad measure of autism symptom severity (Rivière 2002). The authors reported no significant gains in any of the evaluated domains, including those related to social, language and communication skills.

HMD AR

Five studies investigated the use of AR by children, adolescents, and adults with ASD wearing the Brain Power System HMD, later rebranded as Empowered Brain (Keshav et al., 2018; Liu, Salisbury, Vahabzadeh, & Sahin, 2017; Sahin, Abdus-Sabur et al., 2018;

Vahabzadeh, Keshav, Abdus-Sabur, et al., 2018; Vahabzadeh, Keshav, Salisbury, & Sahin, 2018). Participants interacted with others in the physical world and were provided real-time feedback using digital content (e.g., reward graphics, such as a star, appeared when maintaining eye contact). Effect size estimates showed that the intervention led to moderate reductions in participants' social withdrawal and large reductions in inattentiveness and use of inappropriate speech (Liu et al., 2017; Sahin, Abdus-Sabur et al., 2018; Vahabzadeh, Keshav, Abdus-Sabur, et al., 2018; Vahabzadeh, Keshav, Salisbury, et al. 2018). However, it should be noted that effect sizes across these studies ranged from very small to very large. Also, participants in the descriptive single case design study by Keshav et al. (2018) showed improvements in conversation skills, eye contact and classroom participation following AR instruction, but effect size estimates could not be derived for this study.

Feasibility, Barriers and Facilitators of VR/AR

Fifty-three of the included studies yielded findings relevant to the feasibility, barriers, and facilitators of desktop VR (n = 37), HMD VR (n = 7), CAVE VR (n = 1), desktop AR (n = 1), and HMD AR (n = 7). These studies focused predominately on people with ASD (n = 48), with a small number involving people with intellectual disability (n = 2) or people with communication disability (n = 3). Data extracted from studies of quantitative (n = 19), qualitative (n = 15), and mixed methods (n = 19) designs revealed the following content themes: (a) safety, tolerance and acceptance, (b) engagement and navigation within virtual environments, (c) nature of user interactions, (d) barriers to VR/AR, and (e) facilitators of VR/AR.

- Insert Table 4 here -

Safety, Tolerance and Acceptance

Only two studies reported on the safety of using VR/AR with people with neurodevelopmental disorders (Parish-Morris et al., 2018; Sahin, Keshav, Salisbury, &

Vahabzadeh, 2018a; Sahin, Keshav, Salisbury, & Vahabzadeh, 2018b). Adolescents and adults with ASD in the study by Parish-Morris et al. (2018) experienced no serious adverse effects[3] following use of a VR HMD, though some users (7%) did experience minor headaches. A substantial minority of children, adolescents and adults with ASD (6%, 25%) in the studies by Sahin et al. (2018a, b) were found to experience minor headaches but no serious adverse effects after using AR HMDs (Sahin et al., 2018a; Sahin et al., 2018b).

Research attrition rates provide some insight into users' tolerance and acceptance of VR/AR technologies. Several studies in the review reported very low attrition rates for participants with ASD who were invited to use desktop and HMD VR/AR, suggesting these technologies may be well-tolerated (Ke & Im, 2013; Ke & Lee, 2016; Liu et al., 2017; Millen, Cobb, Patel, & Glover, 2014; Parish-Morris et al., 2018; Vahabzadeh, Keshav, Abdus-Sabur et al., 2018; Zhang, Warren, Swanson, Weitlauf, & Sarkar, 2018). However, other studies have reported higher attrition rates (Bernadini et al., 2014; Sahin et al., 2018a; Schmidt, Galyen, Laffey, Babiuch, & Schmidt, 2014; Serret et al., 2014). In addition, none of the included studies considered whether user characteristics (e.g., oral language abilities) or program characteristics (e.g., type of hardware) are associated with VR/AR tolerance.

Engagement and Navigation within Virtual Environments

The reviewed research suggests that once in VR/AR, most people with ASD can navigate virtual environments with relative ease (Cheng, Moore, McGrath, & Fan, 2005; Kandalaft et al., 2013; Kinsella, Chow, & Kushki, 2017; Lan, Hsiao, & Shih, 2018; Weiss et al., 2011). Users with ASD were often found to require no more support than their typically developing peers when learning how to move and interact in the virtual world (Kandalaft et al., 2013; Parsons, 2015; Roper, Millen Dutka, Cobb, & Patel, 2019). Indeed, children, adolescents and adults with ASD tended to exceed expectations in terms of their skills navigating virtual environments presented using VR/AR (Keshav, Salisbury, Vahabzadeh, & Shain, 2017; Lan et al., 2018).

The ability of people with ASD to navigate VR/AR might be related to their level of interest in these technologies. People with ASD frequently reported enjoying and feeling excited about using VR/AR technologies (Cheng et al., 2010; Gallup & Serianni, 2017; Keshav et al., 2018; Kinsella et al., 2017; Lan et al., 2018; Lu et al., 2018; Millen et al., 2014; Weiss et al., 2011; Zhao et al., 2018). Attitudes toward virtual technologies for children, adolescents and adults with ASD were generally positive (Cheng & Huang, 2012; Chung et al., 2015; Ke & Moon, 2018; Lan et al., 2018; Stitcher et al., 2014; Stone, Mills, & Saggers, 2019). For example, guardians in Chung et al. (2015) considered that desktop AR provided positive, enjoyable experiences that were engaging and inherently social for children and adolescents with ASD. Supporters of adults with intellectual disability have also reflected positively on users' engagement with VR but expressed a preference for learning in the physical world where possible (Balandin & Molka-Danielsen, 2015).

People with neurodevelopmental disorders have offered a number of reasons for their enjoyment of VR/AR, including the view that virtual environments can offer safe, controlled, and anxiety-free settings for social interaction. For example, an adult with ASD in Stendal and Balandin (2015) reported "…there's a lot less social anxiety here [in VR]. I can just be myself, and if someone doesn't like it, oh well…" (p. 1595). Adolescents and adults with ASD have also acknowledged that some VR/AR programs provide a context in which they and other users can talk about shared interests "…The only people I talk to are gamers in and out of the game… we get together at cons like the mega-con that was just here in Orlando…" (Gallup, Serianni, Duff, & Gallup, 2016, p. 232). In addition, users with ASD have reported that VR/AR provides a 'common ground' for social interaction and a context in which they can express themselves (Gallup et al., 2016; Gallup & Serianni, 2017; Kinsella et al., 2017).

While most people with neurodevelopmental disorders were able to navigate VR/AR, technological challenges were reported across several studies (Balandin et al., 2015; Chung et al., 2015; Hall, Conboy-Hill, & Taylor, 2011; Ke et al., 2015; Schmidt et al., 2014). Challenges included difficulties operating hardware (e.g., users unintentionally muting headsets) and software malfunctions (e.g., avatars turning into cloud-like shapes). In one of the few studies to investigate the frequency of these challenges, Laffey et al. (2014) noted an average 2.3 instances of technological disruption per 45min session. Disruptions were usually resolved quickly but the authors acknowledged that around a third required specialised technical support (support beyond the skills of a regular classroom teacher). Importantly, while some users were able to persist once technological disruptions were resolved, many users in this study became frustrated. This is consistent with the reports of supporters in Balandin and Molka-Danielsen (2015).

Nature of User Interactions

Sixteen studies on the nature of user interactions in VR/AR yielded information on the potential of these technologies to create authentic communication experiences for people with neurodevelopmental disorders. Observational measures reported in studies of desktop VR indicate that people with ASD engage in restricted patterns of behaviour when immersed in virtual environments to an extent similar to the physical world (Kandalaft et al., 2013; Parsons, Leonard, & Mitchell, 2006, Schmidt et al., 2014; Wang, Laffey, Xing, Galyen, & Sticher, 2017). Relative to typically developing children, children with ASD also exhibited social communication deficits when interacting in VR (Bekele et al., 2014; Bekele et al., 2016; Jarrold et al., 2013; Ke & Lee, 2016; Parsons, Mitchell, & Leonard, 2004; Parsons, 2015; Wallace, Parsons, & Bailey, 2017; Zhao et al., 2018). For example, users with ASD tended to look less frequently at avatars when socially engaged (Jarrold et al., 2013). Users with ASD completed fewer shared actions in collaborative virtual environments (Parsons,

2015) and had difficulty labelling avatar facial expressions (Wallace et al., 2017) and responding to questions and comments relative to their typically developing peers (Zhao et al., 2018). These findings suggest that VR has the potential to recreate authentic communicative experiences for users with ASD and offer environments conducive to social skill development.

Three studies by the same research group investigated the nature of user interactions in HMD VR for adolescents and adults who stutter (Brundage, Brinton, & Hancock, 2016; Brundage, Graap, Gibbons, Ferrer, & Brooks, 2006; Brundage & Hancock, 2015). Participants were found to stutter more frequently in socially challenging interactions presented in VR (e.g., interaction with unsupportive interviewer) relative to less challenging interactions. Measures of stuttering severity were also found to be significantly correlated for social interactions in the physical and virtual worlds (Brundage et al., 2015). These findings show that stuttering presents in a similar way across virtual and physical environments, suggesting that VR may be a useful platform for stuttering assessment and intervention. While participants in these studies reported that virtual worlds felt realistic and that they perceived their stuttering to be similar in the physical and virtual worlds, participants' sense of presence (i.e., state of being absorbed or immersed in VR/AR) was not correlated with stuttering severity in the virtual world.

In addition to the research on stuttering, four studies investigated sense of presence for children and adolescents with ASD using desktop and HMD VR (Beach & Wendt, 2016; Wallace et al., 2017; Wang, Laffey, Xing, Ma, & Stitcher, 2016; Wang, Xing, & Laffey, 2018). These studies identified evidence of embodied presence (i.e., sense of avatar representation of self) and embodied co-presence (sense of avatar representation of other people). For example, one participant in Beach et al. (2016) reflected, "I walked into the hospital and looked around, I was able to run, walk, and sit down. I liked exploring the building…" (p. 29). Sense of presence was associated with avatars' nonverbal interactions in that participants experienced a greater sense of presence if engaged in conversation with other avatars standing face-to-face as opposed to looking away. There is no suggestion that participants were unaware that avatars were not "real" people. Indeed, users with and without neurodevelopmental disorders have been found to have a similar sense of presence in VR (Wallace et al., 2017).

Barriers to VR/AR

Relatively few studies have reported on the potential barriers to using VR/AR with people with neurodevelopmental disorders (Balandin & Molka-Danielsen, 2015; Ke & Moon, 2018; Neale, Leonard, & Kerr, 2002). Some authors have observed that weaknesses in receptive language could negatively impact the ability of adolescents with ASD to carry out instructions in virtual environments, thus preventing users from accessing virtual technologies (e.g., Ke & Moon, 2018). Others have suggested that specific VR/AR design features may discourage users with neurodevelopmental disorders (e.g., Ke & Moon, 2018; Neale et al., 2002). For example, programs which utilise negative feedback were found to unsettle adolescent users with ASD (Neale et al., 2002). Adolescents with ASD were also noted to be overwhelmed when asked to engage in competitive games in multiplayer VR (Ke & Moon, 2018). Lack of time and difficulties managing the physical and virtual worlds in a classroom setting were identified as potential barriers to the implementation of VR/AR in studies of school-based interventions for users with ASD and intellectual disabilities (Balandin & Molka-Danielsen, 2015; Neale et al., 2002).

Facilitators of VR/AR

Most studies which reported on the views and experiences of children, adolescents and adults with neurodevelopmental disorders identified potential facilitators of VR/AR for this population, including external real-world supports and beneficial VR/AR design features.

The presence of a VR/AR support person was identified as a key facilitator for children and adolescents with ASD as well as adults with intellectual disability in studies of desktop and CAVE VR (Cai et al., 2013; Hall et al., 2011). However, there are currently no recommendations regarding the *nature* of support to be provided in VR/AR, although some authors caution users against applying excessive levels of physical support which could impinge on users' movements and interactions in the virtual world (Hall et al., 2011). Pre-instruction training outlining the purposes and requirements of VR/AR was another important facilitator to using VR/AR. For example, children, adolescents, and adults with ASD in the study by Keshav et al. (2018) acknowledged, "I could see if you didn't give that pre-discussion, it could be seen as a toy, try to play with it, take it, and have fights over it." (p. 11).

Several studies identified a need for VR/AR programs to be customisable in order to accommodate the varied needs of users with neurodevelopmental disorders (Andersson & Josefsson, 2008; Lan et al., 2018; Millen et al., 2014; Neale et al., 2002). Suggested parameters for customisability included task difficulty, number of avatar operations (e.g., run, fly, swim), number of user functions (e.g., movement controls, audio input, voice chat, text chat), level of background noise/music, amount of detail in each experience, level of exploration vs. goal-oriented activities, and extent of scaffolded support. Other recommendations relate to the incorporation of physical world supports into virtual environments. For example, inclusion of visual supports (e.g., written 'to do' lists) to help people with ASD carry out instructions (Cheng & Huang, 2012; Ke & Moon, 2018), aligning VR/AR activities with users' interests (Moon & Ke, 2019), and encouraging peer-based interactive learning (Zhao et al., 2018).

Discussion

VR/AR technology has the potential to change and influence the delivery of communication and educational interventions designed for people with disabilities. In this review, we investigated the use of VR and AR technologies in delivering communication interventions for children, adolescents, and adults with neurodevelopmental disorders associated with communication disability (i.e. ASD, intellectual disability, communication disorder, or global developmental delay). Our search of the literature identified 69 studies on the effects of VR/AR interventions for people with neurodevelopmental disorders associated with communication disability and/or the feasibility, barriers and facilitators of these technologies.

Effects of VR/AR Interventions for People with Neurodevelopmental Disorders

Consistent with previous reviews (Bellani et al., 2011; Irish, 2013; Parsons & Mitchell, 2002; Vasquez et al., 2015), we found that VR/AR has the potential to support effective interventions targeting a range of social communication skills for people with ASD and people with intellectual disability. However, results varied greatly both within and across the reviewed studies, and no single VR/AR platform was consistently effective in producing positive intervention outcomes. Since all but one of the reviewed studies investigating the effects of VR/AR interventions focused specifically on children, adolescents and adults with ASD; and only one intervention study involved children, adolescents and adults with intellectual disability, it is clear that further research is needed to inform the evidence-based use of these technologies for individuals with neurodevelopmental disorders.

In the context of mixed results, effect size estimates derived from higher-quality studies indicated that interventions delivered via desktop and tablet VR or VR/AR HMDs tended to be the more effective. For the most part, studies did not reflect on the user or system characteristics that may have influenced intervention outcomes and it was unclear why the CAVE VR, desktop AR, and smartphone AR platforms tended to be less effective than the other VR/AR systems. Nonetheless, the fact that studies using non-immersive (desktop and tablet VR) and fully immersive (HMD VR/AR) technologies reported the most promising intervention outcomes suggests that users' sense of presence or immersion may not be critically important in effective VR/AR communication interventions. This is consistent with the finding that stuttering severity is unrelated to users' sense of presence when immersed in VR (Brundage & Hancock, 2015). Non-immersive VR/AR, which tend to be considerably cheaper and more accessible than other VR/AR technologies, could be used to obtain cost-effective communication gains for children, adolescents, and adults with neurodevelopmental disorders. However, in the absence of rigorous research comparing immersive and non-immersive technologies, it is not possible to provide cost-benefit comparisons in relation to VR/AR interventions.

Outcomes following VR/AR communication interventions were diverse for participants across the different age groups (children, adolescents, adults) and neurodevelopmental disorders, with most studies focusing specifically on people with ASD or intellectual disability. It is not possible to generalise the findings of these studies to children with other conditions, such as cerebral palsy, whose physical impairments and limitations might impact significantly on their use of these technologies. There were also no clear differences in the effects of relatively brief as opposed to more lengthy interventions or among interventions targeting discrete skills (e.g., understanding affect) versus more comprehensive programs (e.g., those targeting multiple aspects of social functioning). Thus, while findings from the included intervention studies suggest that VR and AR have the *potential* to host effective communication interventions for people with neurodevelopmental disorders, these findings do not yet provide sufficient insight into the factors underlying effective VR/AR communication interventions for people in this population.

Feasibility, Barriers and Facilitators of VR/AR

Studies on the feasibility, barriers, and facilitators of VR/AR involving people with ASD, intellectual disability, or communication disorders demonstrate that children, adolescents and adults with neurodevelopmental disorders were willing and able to use VR/AR hardware, including fully immersive HMDs. Once immersed in VR/AR, most people with neurodevelopmental disorders were able to navigate the virtual world with relative ease, and few participants reported adverse effects in the form of minor headaches. Participants with ASD or intellectual disability did require some level of support, though there was evidence that the required supports were no different to those typically provided to other VR/AR users. Overall, these results show that VR/AR is be accessible to many children, adolescents, and adults with neurodevelopmental disorders, but further research is required to clarify which types of supports are needed for successful VR/AR implementation.

Many studies included in the review considered the potential of VR/AR communication interventions with reference to how closely user behaviours in virtual environments aligned with their behaviours in the physical world. There was some evidence that people with neurodevelopmental disorders achieved a sense of presence when immersed in the virtual world; however, it is unclear whether this contributes to the effectiveness of VR/AR interventions. Children, adolescents, and adults with ASD were found to exhibit the same kinds of social communication impairments and restricted patterns of interest in VR/AR that are evident in the physical world (APA, 2013). This suggests that people with neurodevelopmental disorders may experience virtual environments in a way similar to the physical world and that VR/AR may therefore provide authentic opportunities to practice communication and related skills.

Limitations and Directions for Future Research

The vast majority of studies included in the review focused specifically on people with ASD or intellectual disability and programs designed to improve users' social communication skills. Thus, many of the findings may not apply to people with other neurodevelopmental disorders and provide limited insight into the effectiveness of VR/AR interventions targeting other communication skills, such as oral language or fluency. Many of the studies included in the review were of a relatively low quality and it was difficult to identify or compare their key findings (Lorenzo et al., 2013; Lorenzo et al., 2016). Therefore, the findings of this review should be interpreted with caution. Additional high-quality studies are required to better understand the potential of using VR/AR in communication interventions for people with neurodevelopmental disorders. Such research should look to identify and understand both internal user characteristics and external VR/AR features associated with effective communication interventions.

While relatively few studies reported on the potential barriers or facilitators to VR/AR for people with neurodevelopmental disorders, these barriers included a lack of time for supporters to fully implement VR/AR programs and specific VR/AR design features, such as the use of competitive games. The need for a high degree of customisability in VR/AR delivery across multiple parameters, including task difficulty and user functions, is an important area for future research. The extent to which any external physical supports, or verbal prompts, provided to VR/AR experiences might improve or impede the immersive experience would also be important to identify and balance as people with neurodevelopmental disorders might need support either in the external world or internal VR/AR immersive environment in order to participate and be included in future VR/AR interventions.

Conclusion

This systematic review of the research on VR/AR communication interventions for children, adolescents, and adults with neurodevelopmental disorders associated with communication disability shows that VR/AR interventions can be effective in some cases.

However, user outcomes varied both within and across the included studies. Research on the feasibility of VR/AR is sparse. Findings to date suggest that these technologies can be used to create safe and authentic communication learning experiences for the majority of children, adolescents, and adults with ASD, intellectual disability, and communication disorders. Supports in the physical world and within the virtual environment are likely to play an important role in effective VR/AR for these populations. Additional high-quality research involving children, adolescents and adults with a wide variety of neurodevelopmental disorders associated with communication disability is required to determine how VR/AR might be used to address the needs of this highly heterogeneous population. Such research should consider how children, adolescents and adults with neurodevelopmental disorders can be included in research and in the design of VR/AR interventions designed for their use. User-centred co-designed VR/AR applications should include user design and testing that is inclusive of people with communication disability and their supporters, so as to develop and create materials that are meaningful and useful for interventions to improve communication.

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Table 1

Characteristics and Findings of Studies Providing Data on the Effects of VR and AR Interventions

Hardware First author (year)	Participants	Activity (program)	Protocol[a]	Outcomes (measure)[b]	Findings[c]	Quality classification
Desktop VR						
Bernardini (2014)	19 children and adolescents with ASD (4 - 14 years)	Social skills (ECHOES)	1 session (10-20mins) several times a week over 6 weeks	Initiating and responding to social overtures	• No improvement in initiating social overtures (*g* = .02) • No significant improvement in responding to social overtures (*g* = .32)	Higher (74%)
Cheng (2010)	3 children with ASD (7-8 years)	Social scenarios (purpose-built program)	5 sessions (40mins)	Affect recognition and expression, and understanding of social overtures	• Improvement in affect recognition and expression (NAP = 1) • Improvement in understanding of social overtures (NAP = 1)	Lower (50%)
Didehbani (2016)	30 children and adolescents with ASD (7-16 years)	Social scenarios (Second life)	10 sessions (1hr) over 5 weeks	Affect recognition (NEPSY-II, Ekman 60), understanding social overtures (Triangles intentionality)	• Improvement in NEPSY-II affect recognition (*g* = .71) • No improvement in Ekman 60 affect recognition (*g* = .33) • No improvement in understanding social overtures (*g* = .35)	Higher (62%)
Kandalaft (2013)	8 adults with ASD (18-26 years)	Social scenarios (Second Life)	10 sessions (1hr) over 5 weeks	Affect recognition and understanding of social overtures composite (WAIS-IV), affect recognition (The Eyes Test) and conversation skills (SSPA)	• Improvement affect recognition and understanding of social overtures composite (*g* = .57) • No improvement in affect recognition (g = .27) • No improvement in conversation skills (*g* = .46)	Higher (63%)
Ke (2013)	4 children and adolescents with ASD (9-10 years)	Social scenarios (Second Life)	6-9 sessions (1hr)	Initiating and responding to social overtures	• Improvement in initiating social overtures (NAP = .76) • Improvement in responding to social overtures (NAP = .81) • Improvements in specific overtures: turn taking (NAP = .40), greeting (NAP = .74), ending conversation (NAP = .87)	Higher (58%)

Hardware

First author (year)	Participants	Activity (program)	Protocol[a]	Outcomes (measure)[b]	Findings[c]	Quality classification
Ke (2018)	8 adolescents with ASD (10-14 years)	Social scenarios (OpenSim)	16-31 sessions (1hr)	Initiating and responding to social overtures	• No improvement in initiating and responding to social overtures (*g* = .77)	Higher (60%)
Laffey (2014)	11 adolescents with ASD (11-14 years)	Social skills (iSocial)	34 sessions (45mins)	Social skills composite (SRS)	• Improvement in social skills as reported by guardians (*g* = 1.10) • No improvement in social skills as reported by educators (*g* = .38)	Higher (56%)
Mitchell (2007)	6 adolescents with ASD (14-16 years)	Social skills (Virtual Café)	2 sessions (30-50mins) per week over 6 weeks	Understanding social overtures	• Improvement in selecting appropriate seat given avatar social overtures for all participants • Improvement in explaining their seat selection for 4/6 participants	Higher (60%)
Stitcher (2014)	11 children and adolescents with ASD (mean age = 12.57 years)	Social skills (iSocial)	31 sessions (31-45mins) over 4 months	Social skills (SRS), affect recognition (The Eyes Test, DANVA-2), understanding social overtures (The Faux Pas Stories)	• Improvement in social skills as reported by guardians (*g* = 1.16) but not educators (*g* = .37) • No change in affect recognition (*g* = .20, g = .32) or understanding social overtures (*g* = .42)	Higher (86%)
Strickland (2013)	22 adolescents with ASD (16-19 years)	Interview skills (Jobtips)	1 session (30mins)	Interview skills (IRS)	• Improvement in interview content scores for the instruction group relative to the control group • No change in interview delivery scores	Higher (69%)
White (2016)	4 adolescents and adults with ASD (18-22 years)	Affect recognition and social scenarios (Virtual Reality–Brain-Computer Interface for ASD)	7 sessions (25-30mins) over 1.5 months	Social participation and adjustment to college (SACQ)	• No change in school participation and adjustment (*g* = .17)	Higher (67%)
Zhang (2018)	7 children and adolescents with ASD and 21 typically developing children and adolescents (mean age = 10.59, 13.89)	Collaborative play (purpose-built program)	1 session (1hr)	Initiating social overtures	• Increase in frequency of question asking for 2/3 participants • Increase in frequency of other socially oriented utterances for 2/3 participants	Lower (44%)
Zhao (2018)	12 adolescents with ASD and 12 typically	Collaborative play (Hand-in-Hand:	1 session	Time spent playing collaboratively	• Without Communication_Enhancement	Lower (31%)

Hardware First author (year)	Participants	Activity (program)	Protocol[a]	Outcomes (measure)[b]	Findings[c]	Quality classification
	developing adolescents (12-13 years)	Communication-Enhancement System))			mode: no change in collaborative play (g = .39) • With Communication_Enhancement mode: improvement in collaborative play (g = 1.49)	
Tablet VR						
MacCormack (2019)	4 adolescents with ASD (11-13 years)	Social skills (Minecraft)	8 sessions (1hr)	Initiating social overtures, observed play behaviours, guardian reported changes in social behaviour	• Improvement in initiating social overtures (NAP = 1) • Observed change in behaviour from parallel to cooperative play • Parents reported improvements in various social skills	Lower (27%)
CAVE VR						
Ip (2018)	94 children and adolescents with ASD (6-12 years)	Social scenarios (purpose-built program)	28 sessions (40mins) over 14 weeks	Affect recognition (The Faces Test, The Eyes Test), affect expression (PEP-3), social-emotional reciprocity (PEP-3), communication and social functioning (ABAS-II)	• No change in affect recognition (g = .25, g = .18) • Improvement in affect expression (g = .39) • Improvement in social-emotional reciprocity (g = .49) • No change in communication (g = .23) • No change in social functioning (g <.01)	Higher (79%)
Jacques (2018)	3 adults with ASD (age not reported)	Social scenarios (Decoding Social Interaction Task in VR)	1 session	Understanding and responding to social overtures	• Positive trend for understanding and responding to social overture from pre- to post-instruction	Lower (31%)
Lorenzo (2013)	20 children and adolescents with ASD (8-15 years)	Social scenarios (TEVISA supportive tasks protocol)	80 sessions (25mins) over 40 weeks	Executive and social skills composite (PIAV)	• Understanding of and ability to carry out tasks in VR varied from task to task • Gradual improvement in body coordination control, voice control, eye control, attention control and empathy control	Lower (36%)
Lorenzo (2016)	40 children and adolescents with ASD (7-12 years)	Social scenarios (purpose-built program)	4 sessions (35mins) over 4 months	Social skills composites	• Increase in frequency of ‘adequate behaviours’	Lower (48%)

Hardware First author (year)	Participants	Activity (program)	Protocol[a]	Outcomes (measure)[b]	Findings[c]	Quality classification
HMD VR						
Cheng (2015)	3 adolescents with ASD (10-13 years)	Social scenarios (purpose-built program)	1 session (30-40mins) per week over 6 weeks	Understanding and initiating social overtures	• Improvement in understanding (NAP = 1) • Improvement in initiating social overtures (NAP = 1)	Lower (52%)
Desktop AR						
Burke (2018)	22 adolescents and adults with ASD (19-31 years)	Interview skills (Virtual Interactive Training Agent)	4 sessions over 14 weeks	Interview skills composite	• Improvement in interview skills for ASD group (p < .01)	Lower (55%)
Byrne (2015)	72 children, adolescents, and adults with intellectual disabilities (6-20 years)	Social scenario (Interactive Sensory Program for Affective Learning)	32 sessions over 18 months	School participation (SFA)	• Improvement in school participation (g = .22)	Lower (31%)
Chen (2015)	3 adolescents with ASD (10-13 years)	Affect recognition (AR-Based Self-Facial Modeling Learning System)	7 sessions (25-30mins) over 1.5 months	Affect recognition	• Improvement in affect recognition (NAP = 1)	Lower (29%)
Chung (2015)	3 children and adolescents with ASD (8-12 years)	Shared play using commercially available games (Star Wars, Disney University, Fruit Ninja, and Connect Party)	12 sessions (30mins) in dyad with typically developing sibling	Affect expression and conversation skills	• Increase in positive affect expression (NAP = .57) • Improvement in conversation skills (NAP = .43)	Higher (63%)
Smartphone AR						
Lorenzo (2019)	11 children with ASD (2-6 years)	Social scenarios (Quiver Vision)	2 sessions (15mins) per week over 20 weeks	Autism severity (ASI) – results reported separately for each test item	• No changes in social skills in any domain (median g = .12)	Lower (48%)
HMD AR						
Keshav (2018)	1 adolescent with ASD (13 years)	Social skills (Brain Power Autism System)	4 sessions over 2 weeks	Observed social communication and reading skills	• Educators reported improvements in conversation skills, eye contact and participation during classroom activities	Higher (60%)
Liu (2017)	2 children with ASD (8,9 years)	Social skills (Brain Power Autism System)	1 session	Lethargy/social withdrawal,	• Guardians reported reduction in lethargy/social withdrawal (g = 1.05)	Lower

Hardware

First author (year)	Participants	Activity (program)	Protocol[a]	Outcomes (measure)[b]	Findings[c]	Quality classification
				inappropriate speech (ABC)	hyperactivity/ inattention (g = 2.34), and inappropriate speech (g = 1.79)	(44%)
Sahin, Abdus-Sabur (2018)	1 adolescent with ASD (13 years)	Social skills (Brain Power Autism System)	16 sessions over 2 weeks	Social skills composite (SRS-2)	• Improvements in social skills as rated by educators and guardian	Lower (52%)
Vahabzadeh, Keshav, Abdus-Sabur, et al. (2018)	4 children with ASD (6-9 years)	Social skills (Empowered Brain)	2 sessions (10mins) over 2 weeks	Lethargy/social withdrawal, hyperactivity/ inattention, inappropriate speech (ABC)	• Teacher and speech pathologist reported reduction in lethargy/social withdrawal (g = .57, g = .29), hyperactivity/inattention (g = 1.24, g = .36) and inappropriate speech (g = 1.61, g = .26)	Lower (55%)
Vahabzadeh, Keshav, Salisbury et al. (2018)	8 adolescents, and adults with ASD (11-20 years)	Social skills (Empowered Brain)	1 session (10-20mins)	Hyperactivity/inattention (ABC)	• Guardians reported reduction in hyperactivity/ inattention (g = .44)	Lower (43%)

[a]Protocol details including session number and duration, and number of weeks are reported where known.
[b]Name of measure is reported where known otherwise a description is provided.
[c]Standard effect size measures (g or NAP) are reported where able to be computed using information reported in text (e.g., descriptives). Only communication-related outcomes are reported. NAP data are mean scores across participants. NAP scores of 0-0.65, 0.66-0.92, and 0.92-1.0 are considered to reflect weak, medium, and strong effects respectively (Parker & Vannest, 2009).
Note. ABAS-II: Adaptive Behavior Assessment - 2nd edition (Harrison & Oakland, 2003). ABC: Aberrant Behaviour Checklist (Aman, Singh, Stewart, & Field, 1985). DAVNA-2: Diagnostic Analysis of Von-Verbal Accuracy - 2nd edition (Nowicki and Carton 1993). ASI: Autistic Spectrum Inventory (Rivière, 2002). Ekman 60: Facial Expressions of Emotion Stimuli and Tests (Young, Perrett, Cabler, Sprengelmeyer, & Ekman, 2002). IRS: Interview Rating Scale (Strickland, Coles, & Southern, 2013). NEPSY-II: Developmental NEuroPSYchological Assessment - 2nd edition (Korkman, Kirk, & Kemp, 2007). PEP-3: Psychoeducational Profile – 3rd edition (Schopler, Lansing, Reichler, & Marcus, 2004). PIAV: Instructional Protocol of Avatars (Lorezno, Pomares, & Lledó, 2013). SACQ: Student Adaptation to College Questionnaire (Baker & Siryk, 1999). SFA: School Function Assessment (Coster, Mancini, & Ludlow, 1999). SRS: Social Responsiveness Scale (Constantino & Gruber, 2005). SRS-2: Social Responsiveness Scale - 2nd edition (Constantino & Gruber, 2012). SSPA: Social Skills Performance Assessment (Patterson, Moscona, McKibbin, Davidson, & Jeste, 2001). The Eyes Test (Baron-Cohen, Wheelwright, &, Hill, Raste, & Plumb, 2001). The Faces Test (Baron-Cohen, Wheelwright, &, Hill, Raste, & Jolliffe, 1997). The Faux Pas Stories (Baron-Cohen, O'Riordan, Stone, Jones, & Plaisted, 1999). Triangles Intentionality (Abell, Happe`, & Frith, 2000). WAIS-IV: Wechsler Adult Intelligence Scale - 4th edition (Wechsler, 2008).

Table 2

Summary of VR Intervention Outcomes (Standardised Effect Sizes) by Platform

Platform Outcome	Group design studies (*g*)		Single subject design studies (NAP)	
	Median	Range	Median	Range
Desktop VR				
General social skills	.74	.37 - 1.16	-	-
Understanding social overtures	.42	.35 - .57	1	1
Response to social overtures	.55	.32 - .77	.81	.81
Initiating social overtures	.40	.02 - .77	.88	.76 - 1
Affect recognition	.32	.20 - .71	1	1
Affect expression	-	-	1	1
Conversation skills	.46	.46	-	-
Collaborative play skills	94	.39 - 1.49	-	-
School participation and adjustment	.17	.17	-	-
Tablet VR				
Initiating social overtures	-	-	1	1
CAVE VR				
General social skills	<.01	<.01	-	-
General communication skills	.23	.23	-	-
Affect recognition	.22	.18 - .25	-	-
Affect expression	.39	.39	-	-
Social-emotional reciprocity	.49	.49	-	-
VR HMD				
Understanding social overtures	-	-	1	1
Initiating social overtures	-	-	1	1

Table 3

Summary of AR Intervention Outcomes (Standardised Effect Sizes) by Platform

Platform	Group design studies (*g*)		Single subject design studies (NAP)	
Outcome	Median	Range	Median	Range
Desktop AR				
Affect recognition	-	-	1	1
Affect expression	-	-	.57	.57
Conversation skills	-	-	.43	.43
School participation	.22	.22	-	-
Smartphone AR				
General social skills	.12	.12	-	-
HMD AR				
Lethargy/social withdrawal	.57	.29 - 1.05	-	-
Hyperactivity/inattention	.84	.36 - 2.34	-	-
Inappropriate speech	1.61	.26 - 1.79	-	-

Table 4

Characteristics of Studies Providing Feasibility, Barriers, and Facilitators Data by Type of VR and AR Hardware

Hardware First author (year)	Research design	Participants	Activity (program)	Data collection methods	Data description	Quality classification
Desktop VR						
Andersson (2006)	Qualitative	21 children, adolescents, and adults with ASD (6-21 years)	General VR use	Literature review, user interview, and expert consultation	Researcher recommendations for VR design	Higher (74%)
Balandin (2015)	Qualitative	5 assistants working with 10 adults with intellectual disability (age not reported)	Social scenarios (Second life)	Educator interview	Barriers, facilitators, and future opportunities for VR use	Higher (62%)
Bekele (2013)	Quantitative	10 adolescents with ASD typically developing peers (13-17 years)	Identifying facial expressions (purpose-built program)	VR observation (gaze tracking, eye physiological data, accuracy and latency of facial expression identification, and confidence in facial expression judgements)	Nature of emotion recognition and social attention	Lower (45%)
Bekele (2014)	Quantitative	10 adolescents with ASD and 10 typically developing adolescents (13-17 years)	Identifying facial expressions (purpose-built program)	VR observation (gaze tracking, eye physiological data, accuracy and latency of facial expression identification, and confidence in facial expression judgements)	Nature of emotion recognition and social attention	Higher (64%)
Bernardini (2014)	Quantitative	19 children and adolescents with ASD (4 - 14 years)	Social skills (ECHOES)	Research field notes	Attrition from VR intervention	Higher (74%)
Cheng (2005)	Quantitative	10 children and adolescents with ASD (8-17 years)	Identifying facial expressions (purpose-built program)	VR observation (general researcher comments)	Number of participants who "performed well" as determined by researcher	Lower (14%)
Cheng (2010)	Mixed	3 children with ASD (7-8 years)	Social scenarios (purpose-built program)	Guardian questionnaire and interview	VR acceptability, social interaction in VR, and opportunities for future VR	Lower (50%)
Cheng (2012)	Mixed	3 children and adolescents with ASD (9-12 years)	Social skills (purpose-built program)	Guardian questionnaire	VR acceptability, user enjoyment, and opportunities for VR use	Lower (25%)

Hardware First author (year)	Research design	Participants	Activity (program)	Data collection methods	Data description	Quality classification
Gallup (2016)	Qualitative	3 adolescents and adults with ASD (16-21 years)	Free play (MMORPGs)	User interview and focus group	AR acceptability and social interaction in VR	Higher (62%)
Gallup (2017)	Qualitative	5 adolescents and adults with ASD (19-24 years)	Free play (MMORPGs)	User interview, observation of VR gameplay, and blogs, forums and chat boxes from VR gameplay	Social interaction in the real world and VR	Higher (67%)
Hall (2011)	Qualitative	20 adults with intellectual disabilities (20-80 years)	Social scenarios (Second life)	User interview and VR observation (user acceptability)	Time taken to engage with VR, physical access to VR, and key contextual factors	Higher (79%)
Kandalaft (2013)	Mixed	8 adolescents and adults with ASD (18-26 years)	Social scenarios (Second Life)	User interview and questionnaire, and VR observation (user acceptability)	Enjoyment and ease of VR use, social interactions in VR and the real world, efficacy of VR intervention	Higher (63%)
Ke (2013)	Mixed	4 children and adolescents with ASD (9-10 years)	Social scenarios (Second Life)	Guardian interview and VR observation (user acceptability)	Guardian satisfaction and ability to navigate VR	Higher (58%)
Ke (2015)	Qualitative	8 adults working with children and adolescents with ASD (9-10 years)	Social scenarios (Second life)	Educator interview and VR observation (user engagement and VR facilitation)	VR barriers and facilitators	Higher (62%)
Ke (2016)	Mixed	2 children and adolescents with ASD and 1 typically developing child (8, 10 years)	Social scenarios (OpenSim)	VR observation (user acceptability and social interactions)	Number of participants able to complete tasks in VR and frequency of social interactions in VR	Higher (71%)
Ke (2018)	Mixed	8 adolescents with ASD (10-14 years)	Social scenarios (OpenSim)	VR observation (user acceptability) and user interview	User enjoyment, session completion, and VR barriers and facilitators	Higher (60%)
Laffey (2014)	Mixed	11 adolescents with ASD (11-14 years)	Social skills (iSocial)	VR observation (technology issues)	Incidence of technological disruption	Higher (56%)
Lan (2018)	Qualitative	1 child with ASD, 2 children with ADHD, 1 child with "mental retardation" (8-9 years)	Language skills (Second life)	VR observation (user acceptability) and user interview	Researcher recommendations for VR design	Lower (43%)
Lu (2018)	Mixed	10 children and adolescents with ASD and 2 children and	Gestural communication skills (Virtual pink dolphin game)	VR observation (user acceptability) and user interview	Session completion, user enjoyment and preferences	Lower (26%)

Hardware First author (year)	Research design	Participants	Activity (program)	Data collection methods	Data description	Quality classification
		adolescents with "special needs" (8-16 years)				
Millen (2014)	Qualitative	12 adolescents with ASD (11-14 years)	Participatory design (Island of Ideas)	VR observation (user acceptability) and user questionnaire	Session completion, user preferences (Likert scale), and ideas for improving VR	Lower (40%)
Moon (2019)	Mixed	15 adolescents with ASD (10-14 years)	Social scenarios (OpenSim)	VR observation (social interaction)	Nature of social interactions in VR and VR barriers and facilitators	Lower (56%)
Neale (2002)	Qualitative	8 adolescents with ASD (16-19 years)	Social skills (purpose-built program)	VR and real-world observation (social interaction) and educator interview	VR barriers and facilitators	Lower (57%)
Parsons (2004)	Mixed	12 adolescents with ASD, 12 typically developing children (matched verbal IQ), and 12 typically developing children (matched performance IQ)	Social skills (purpose-built program)	VR observation (social interaction)	Nature of social interactions in VR	Lower (40%)
Parsons (2006)	Qualitative	2 adolescents with ASD (14,17 years)	Social skills (purpose-built program)	VR observation (social interaction)	Nature of social interactions in VR	Lower (45%)
Parsons (2015)	Quantitative	6 children and adolescents with ASD and 8 typically developing children and adolescents (7-13 years)	Social skills (purpose-built program)	VR observation (social interaction)	Nature of social interactions in VR	Higher (76%)
Roper (2018)	Mixed	12 adolescents with HFASD and 4 adolescents with ASD (12-14 years) and 12 typically developing children (8-9 years)	Participatory design (purpose-built program)	VR observation (user acceptability) and user questionnaire	VR session completion and user preferences	Lower (54%)
Schmidt (2014)	Qualitative	Study 1: 2 adolescents with ASD (11,13 years) Study 2: 4 adolescents with ASD (12-13 years) Study 3: 2 adolescents with ASD (13,14 years) Study 4: 4 adolescents with ASD (12-14 year)	Social skills (Free/Open Source Software)	VR observation (user acceptability and social interactions in VR and the real-world)	VR barriers and facilitators, and nature of social interactions in VR and the real world	Lower (50%)

Hardware First author (year)	Research design	Participants	Activity (program)	Data collection methods	Data description	Quality classification
		Study 5: 6 adolescents with ASD (12-14 years)				
Serret (2014)	Mixed	33 children and adolescents with ASD (6-17 years)	Social skills (JeStiMuLE)	VR observation (user acceptability)	Session completion and ability to move in VR	Lower (48%)
Stendal (2015)	Qualitative	1 adult with ASD	Social skills (Second life)	User interview	VR acceptability, barriers, facilitators, and future opportunities	Higher (69%)
Stitcher (2014)	Quantitative	11 children and adolescents with ASD (mean age = 12.57 years)	Social sills (iSocial)	Guardian, educator, and user questionnaire	Guardian, educator, and user satisfaction	Higher (86%)
Stone (2019)	Qualitative	3 children and adolescents with ASD (9-10 years)	Free play (Minecraft)	VR observation (social interaction) and educator interview	VR acceptability and nature of social interactions in VR	Higher (71%)
Wallace (2017)	Quantitative	10 adolescents with ASD and 10 typically developing adolescents (12-16 years)	Social skills (purpose-built program)	VR observation (facial expression recognition) and user questionnaire	Accuracy of facial expression identification and sense of presence in VR	Higher (76%)
Wang (2016)	Quantitative	11 adolescents with ASD (11-14 years)	Social skills (iSocial)	VR observation (social interaction and evidence of presence in VR)	Nature of social interaction in VR	Lower (52%)
Wang (2017)	Quantitative	11 adolescents with ASD (11-14 years)	Social skills (iSocial)	VR observation (social interaction)	Nature of social interactions in VR	Higher (69%)
Wang (2018)	Quantitative	11 adolescents with ASD (11-14 years)	Social skills (iSocial)	VR observation (social interaction)	Nature of social interactions in VR	Higher (57%)
Weiss (2011)	Quantitative	12 children and adolescents with ASD (9-13 years)	Social skills (TalkAbout)	User and therapist questionnaire (user and therapist acceptability)	VR user enjoyment and understanding of VR tasks, and therapist rated usability	Lower (40%)
Zhang (2018)	Mixed	7 children and adolescents with ASD and 21 typically developing children and adolescents (mean age = 10.59, 13.89)	Cooperative play (purpose-built program)	VR observation (user acceptability) and user questionnaire	Session completion and VR user enjoyment	Lower (44%)
Zhao (2018)	Mixed	12 children and adolescents with ASD and 12 typically developing children and adolescents (12-13 years)	Collaborative play (Hand-in-Hand: Communication-enhancement System)	User questionnaire (user acceptability)	VR user satisfaction, and barriers and facilitators	Lower (31%)

Hardware First author (year)	Research design	Participants	Activity (program)	Data collection methods	Data description	Quality classification
CAVE VR						
Cai (2013)	Quantitative	15 children and adolescents with ASD (6-17 years)	Nonverbal communication skills (purpose-built program)	VR observation (user acceptability)	VR task completion and facilitators	Higher (57%)
HMD VR						
Beach (2016)	Qualitative	1 adolescent and 1 adolescent with ASD (15,18 years)	Social scenarios (Second Life)	User interview and journals and research field notes	Social interactions in VR	Lower (52%)
Brundage (2006)	Mixed	23 adults who stutter (20-52 years)	Stuttering (The Virtual Reality Job Interview)	VR observation (stuttering severity) and user interview	Nature of stuttering and sense of presence in VR	Higher (58%)
Brundage (2015)	Mixed	10 adults who stutter (23-52 years)	Virtually better program	VR observation (stuttering severity)	Nature of stuttering and sense of presence in VR	Higher (58%)
Brundage (2016)	Quantitative	10 adolescents and adults who stutter (18-51 years)	Stuttering (purpose-built program)	VR observation (anxiety and stuttering severity)	Objective anxiety measures (heart rate, skin conductance), subjective anxiety measure (distress scale), and nature of stuttering in VR	Higher (76%)
Jarrold (2013)	Quantitative	37 children and adolescents with ASD and 54 typically developing children and adolescents (8-16 years)	Social skills (The Virtual Social Attention, Public Speaking Task)	VR observation (social attention – gaze)	Nature of social attention in VR	Higher (79%)
Parish-Morris (2018)	Quantitative	28 adolescents and adults with ASD (12-37 years)	Interactions with police training (Floreo Police Safety Module)	VR observation (user acceptability) and suer questionnaire and interview	VR session completion, adverse effects and usability ratings	Lower (46%)
Desktop AR						
Chung (2015)	Quantitative	3 children and adolescents with ASD (8-12 years)	Shared play using a range of commercially available AR games (i.e., Star Wars, Disney University, Fruit Ninja, and Connect Party)	Guardian survey (general impression)	Guardian impressions of AR in terms of child enjoyment, frustration and engagement.	Higher (63%)

Hardware First author (year)	Research design	Participants	Activity (program)	Data collection methods	Data description	Quality classification
HMD AR						
Keshav (2017)	Quantitative	21 children, adolescents and adults with ASD (4-22 years)	Social skills (Brain Power Autism System)	AR observation (user acceptability) and guardian questionnaire	User and guardian acceptability	Lower (50%)
Keshav (2018)	Qualitative	1 adolescent with ASD (13 years)	Social skills (Brain Power Autism System)	Educator interview and teaching logs	Educator acceptability and perception of AR	Higher (60%)
Kinsella (2017)	Quantitative	15 children and adolescents with ASD (8-16 years)	Social skills (Holli)	AR observation (program functioning), user survey and interview	AR program functioning and user satisfaction	Higher (65%)
Liu (2017)	Mixed	2 children with ASD (8,9 years)	Social skills (Brain Power Autism System)	Guardian interview	User enjoyment and acceptability	Lower (44%)
Sahin (2018a)	Mixed	18 children, adolescents and adults with ASD (4-22 years)	Social skills (Brain Power Autism System)	AR observation (user acceptability) and user and guardian interview	User acceptability, adverse effects, and guardian acceptability	Lower (55%)
Sahin (2018b)	Mixed	8 children and adolescents with ASD (6-17 years)	Social skills (Brain Power Autism System)	AR observation (user acceptability) and user and guardian interview	User acceptability, adverse effects, and guardian acceptability	Lower (38%)
Vahabzadeh, Keshav, Abdus-Sabur, et al. (2018)	Quantitative	4 children with ASD (6-9 years)	Social skills (Empowered Brain)	AR observation (user acceptability) and educator interview	User and educator acceptability	Lower (55%)

Footnotes

[1]Analysis using the QATSDD framework is not intended to yield overall ratings of research rigor. Instead, ratings differentiate lower- and higher-quality studies within a given field.

[2]Individuals 5-9 years are considered children, 10-19 years are considered adolescents, and 20+ years are considered adults (World Health Organisation, 2014).

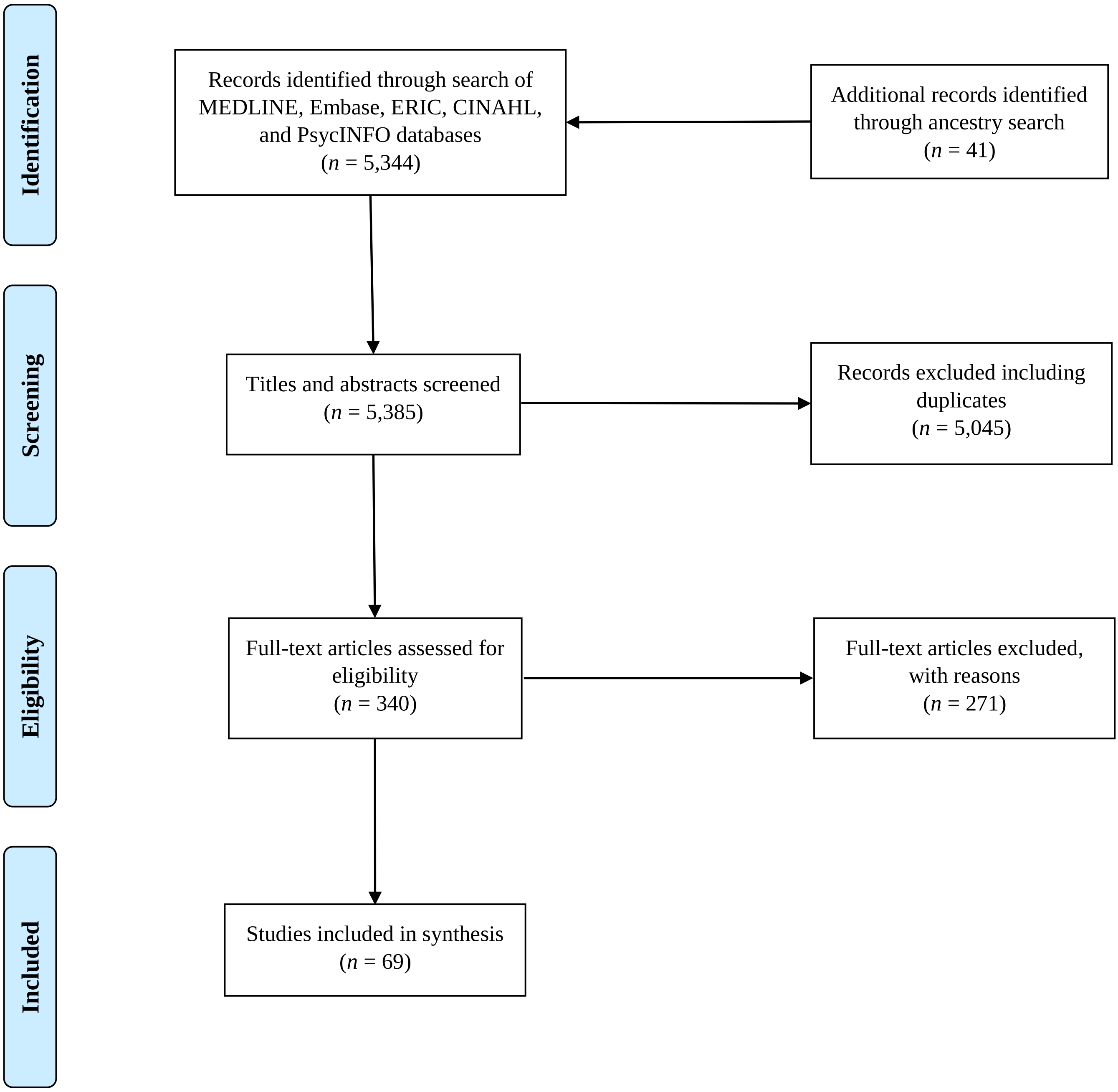
[3]Sixteen studies reported on both the feasibility and effects of VR and AR. Thus, the combined number of studies appearing under the Effects of VR/AR Interventions and Feasibility, Barriers and Facilitators of VR/AR subheadings does not equal the total number of studies included in the review.

[4]‘Serious adverse effects’ were defined as events requiring a hospital visit.

Figure Caption

Figure 1. Flow chart of search strategy based on PRISMA flow diagram.

Figure 1 top


Identification
Screening
Eligibility
Included
Records identified through search of MEDLINE, Embase, ERIC, CINAHL, and PsycINFO databases (n = 5,344)
Additional records identified through ancestry search (n = 41)
Titles and abstracts screened (n = 5,385)
Records excluded including duplicates (n = 5,045)
Full-text articles assessed for eligibility (n = 340)
Full-text articles excluded, with reasons (n = 271)
Studies included in synthesis (n = 69)