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Systematic Literature Review of Virtual Reality Intervention Design Patterns for Individuals with Autism Spectrum Disorders

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ABSTRACT

The aims of this systematic literature review were to uncover, analyze, and present design characteristics of virtual reality (VR) systems that have been designed as training tools for individuals with autism. Specifically, this review sought to (1) assess points of convergence and divergence in how researchers define VR, (2) extrapolate individual components of VR systems, and (3) systematically extract how design factors are instantiated in these VR projects. A systematic review was conducted to approach these goals that followed the Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) standards to provide methodological and reporting quality. English language papers published in peer-reviewed academic journals after 1995 were included. Databases searched for this systematic review were Web of Science, PubMed, Scopus, IEEE Xplore, ERIC, and Google Scholar. Searches were conducted in March, 2020. A total of 82 articles was analyzed which were organized by project, resulting in a total of 49 records. Findings from this literature review suggest inconsistencies in how VR is being conceptualized which has implications on how purported benefits of VR technologies may be designed for and greatly impact the possibilities for learner interactions and how benefits can be realized. Open Science Foundation registration:osf.io/5asyg.

1. Rationale

The effectiveness of virtual reality (VR) for individuals with autism spectrum disorder (ASD) has been discussed at length in the literature (Karami et al., 2021; Mesa-Gresa et al., 2018; Parsons, 2016). Although researchers hypothesize that VR could be a highly effective training, therapeutic, and intervention modality, extant systematic literature reviews and meta analyses suggest only moderate effects (Karami et al., 2021). This mismatch between anticipated and actual effectiveness has been attributed to methodological limitations, including small sample sizes, limited use of control groups, and a lack of longitudinal research (Parsons, 2016). However, absent in the discourse are considerations of how the design of VR technology might influence the effectiveness of interventions. Interrogating the question of technology design reveals substantial disparity in how researchers in this area conceive of and characterize VR as a whole, as well as how VR interventions for individuals with ASD are designed. For example, some researchers have classified driving simulations (e.g. Wade et al., 2016) and conversational agents (e.g. Chen et al., 2019) as VR. The lack of consensus around what constitutes VR and significant dissimilarities across intervention designs confounds efforts to generalize findings, generate theory, and translate research to practice. This paper therefore has two aims. First, we seek to explore how researchers in this area characterize and define VR. Second, we seek to uncover, analyze, and present the design characteristics of VR systems that have been designed as intervention or training tools for individuals with ASD. To these ends, we conducted a systematic literature review, based on PRISMA guidelines, and informed by frameworks suggested by prominent scholars of VR in general (Dalgarno & Lee, 2010) and VR for ASD, specifically (Parsons, 2016).

Autism Spectrum Disorder (ASD) is a lifelong neurodevelopmental disorder associated with deficits in communicative and social interactions, as well as restrictive and stereotyped behaviors (*DSM-5 American Psychiatric Association. Diagnostic and Statistical Manual of Mental Disorders*, 2013) that impacts an estimated 1 in 59 children in the United States (Baio et al., 2018). Autism is considered a spectrum-based disorder with symptoms presenting differently in everyone (DSM-5 American Psychiatric Association, 2013), and with other psychopathological comorbidities tending to be prevalent (Müller et al., 2008). These impairments can severely impact an individual's quality of life resulting in social isolation, difficulties maintaining employment, and mental health issues (Eaves & Ho, 2008; Hedley et al., 2017) which has led to a need for effective and appropriate interventions to help develop skills needed to thrive in social contexts (Bellani et al., 2011; Rao et al., 2008). Technology-aided instruction has been seen as particularly viable for this population and has gained the support of The National Professional Development Center on Autism Spectrum Disorder (Bogin,

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2008). One technology that has been growing in interest to be used with this population is virtual reality (VR) as evidence suggests that the visually stimulating nature of the modality is intrinsically reinforcing for people with ASD (Schmidt et al., 2019).

VR is "a model of reality with which a human can interact, getting information from the model by ordinary human senses such as sight, sound, and touch and/or controlling the model using ordinary human actions such as position" (Hale & Stanney, 2014, p. 34) and typically includes a digitally simulated three-dimensional space that can induce sensations of telepresence (Miller & Bugnariu, 2016) including both the physical sensations delivered through computer generated sensory stimuli and the psychological sense of feeling 'there' within a computer-generated virtual environment (Slater et al., 2009; Steuer, 1992). A high degree of interaction and immersion is typically provided through VR systems that can translate a user's actions into a virtual environment (Bozgeyikli et al., 2018). This effect is often achieved through a user's control of an avatar, which acts as a nexus of interaction within the virtual world, allowing for a degree of psychological immersion or a sense of embodiment (Kilteni et al., 2012). Researchers have investigated a range VR systems for ASD including (1) desktop-based systems, (2) projection-based systems, (3) cave automatic virtual environments (CAVE), (4) fully immersive HMD-based systems, and (5) mobile-based systems (Bozgeyikli et al., 2018; Shu et al., 2019). These VR systems are used to provide users a medium to interact with and within a virtual environment such as a three-dimensional virtual world, which are seen as being beneficial for providing instruction and assessment (cf. Dalgarno & Lee, 2010) and especially so for individuals with ASD. Due to the affordances of this technology, researchers are increasingly looking toward VR as a means to provide interventions for this population (Aresti-Bartolome & Garcia-Zapirain, 2014) following seminal work that assessed how young children with ASD might accept head-mounted displays (HMD) while engaging in a virtual environment (Strickland, 1996).

1.1. Problems of overgeneralization in the literature

Generally speaking, the outcomes of research on VR for individuals with ASD are promising and suggest a moderate degree of effectiveness. However, questions linger concerning whether extant empirical evidence is sufficient to support claims of effectiveness (Parsons, 2016). Research summaries and syntheses in this research area point to the potential benefits of using VR with this population (Karami et al., 2021; Mesa-Gresa et al., 2018). ASD is widely accepted as being a complex, pervasive, heterogeneous condition with a wide range of etiologies, subtypes, and developmental trajectories (Masi et al., 2017). Summarizing and synthesizing research findings from disparate approaches to intervention that implement a broad variety of VR technologies for this extraordinarily heterogeneous population requires particular care so as to avoid overgeneralizing findings. First, generalization of specific findings from research performed with a subset of individuals with ASD to the entire ASD population is methodologically unsound. Indeed, a recognized limitation of research in this area is limited sample sizes and a general lack of control groups (Parsons, 2016). Findings from studies with adolescents or children with ASD in need of low levels of support (the focus of most research) cannot generalize to adults, those who are in need of more substantial support, or those presenting more severe comorbidities. Broad claims that VR can be an efficacious tool for individuals with ASD must therefore be reexamined from this perspective and correspondingly tempered (DSM-5 American Psychiatric Association, 2013; Müller et al., 2008). Second, VR technologies used in interventions are not homogenous (Skarbez et al., 2017); they use a constellation of different technologies, with differing affordances and constraints. Interactions afforded to individual users by a given system's interaction possibilities and underlying design significantly influence performance outcomes. Parsons (2016) suggests there is likely no VR system, technology, or associated affordance (e.g., immersion, sense of presence) that independently influences intervention efficacy for individuals with ASD and calls for researchers to consider 'which technologies work for whom, in which contexts, with what kinds of support, and for what kinds of tasks or objectives?' (p. 153). Therefore, it is unclear if findings from systematic literature reviews suggesting the effectiveness of VR for ASD can be extrapolated to all VR system types.

1.2. Problems with generalization to novel contexts

Generalization is seminally defined by Stokes and Osnes (2016) as the "outcome of behavior change and therapy programs, resulting in effects extraneous to original targeted changes" (p. 338). To address concerns of generalization, designers of VR systems for this population have historically looked in one direction, "towards a closer fit with the real world in order to assess cognition and support the generalization of learning" (Parsons, 2016, p. 154). However, establishing evidence of generalization from virtual to real contexts remains elusive. Indeed, generalization is widely recognized as perhaps the most prominent limitation in all autism research (Arnold-Saritepe et al., 2009; Neely et al., 2016). Designing VR systems to closely mimic the real world so as to promote generalization rests on the "assumption of veridicality;" that is, if experiences within VR worlds are authentic and sufficiently realistic, users of these VR systems will behave in the virtual world in a similar way as they do in the real world, thereby increasing the likelihood that skills learned in the virtual world will transfer to the real world (Parsons, 2016; Yee et al., 2007). This premise rests on a further assumption of intuition, that is, greater fidelity of a VR world will lead to a greater sense of telepresence and therefore generalization (Dalgarno & Lee, 2010). These assumptions have not yet been seriously empirically explored, leading to criticism as there is no sufficient evidence to support the claim that learners will trust their experiences within a VR world to sufficiently reorganize their mental models of the real world (Dalgarno & Lee, 2010) and thereby apply lessons learned in a VR intervention into naturalistic contexts. Technology alone may be insufficient to promote generalization (Parsons, 2016). Designers must consider the interplay of tasks, environments, participants, and technology, as well as how to introduce and fade performance supports and scaffolds in the VR environment so as to promote generalization (Stokes & Osnes, 2016). This suggests a need for more intentional intervention design so as to promote generalization, yet researchers have yet to address this issue in published research.

1.3. Inherent complexity of designing VR interventions for individuals with ASD

We argue a more careful consideration of VR systems design is needed if researchers are to meaningfully confront the unique challenges that individuals with ASD face in general and difficulties with generalization specifically. If VR is to be used as a social-psychological tool (Blascovich et al., 2002), then the affordances of the technology that are being used and how they influence performance need to be better understood (Parsons, 2016). This represents a significant challenge, as designing VR systems for individuals with ASD, as characterized by Schmidt (2014), is a "wicked problem."

> [Designing VR systems for individuals with ASD] is an ill-structured problem for which there may be no comprehensive solution. The problem appears to be wicked because, on the one hand, our knowledge of the problem in general is incomplete and perhaps in some ways contradictory. On the other hand, the problem is interconnected with a plethora of other problems, and solving one problem may exacerbate another. (p. 68).

Designers of VR interventions face significant challenges in creating effective and usable products, as they have to make many decisions concerning design that have no "correct" solution (Glaser et al., 2021; Sherman & Craig, 2002). One of the challenges in designing a VR intervention is determining how users will interact with the system to exploit the affordances of the technology. Unfortunately, much of what has been published concerning the use of VR technologies is largely 'show-and-tell' with evidence being anecdotal and unable to be generalized to other system contexts. Dalgarno and Lee (2010) suggest two distinguishing characteristics of VR technology that can impact learning: (1) representational fidelity and (2) learner interaction. Some have interpreted this to imply that tweaking representational fidelity and learner interactions will innately lead to improved learning outcomes (Fowler, 2015). However, this suggestion is not empirically validated. There are currently no standards in place to determine how these characteristics can be brought together to promote learning (Dalgarno & Lee, 2010; Parsons, 2016). Considerations of how to influence performance begin with understanding underlying VR architectures, which in turn can impact what interaction possibilities are afforded to users of the system (i.e., affordances; Gibson, 2014). Various VR system architectures present their own sets of unique affordances and constraints, thereby impacting design considerations of how to best harness potentially useful characteristics of the technology (Dalgarno & Lee, 2010). If researchers are to approach the problem of how to design effective VR interventions for individuals with ASD in an intentional way, then an operational definition of VR for this field is needed. To inform this operationalization, an understanding of how VR systems have been designed to exploit the characteristics of the technology is needed. This again points to the need to explore which technologies work, for whom, under which contexts, with what kinds of support, and for what kinds of objectives (Parsons, 2016).

1.4. Research purpose and questions

To summarize, VR is seen as a promising modality to deliver instruction for individuals with ASD, and reviews of the literature in this research area point to potential benefits (Karami et al., 2021; Mesa-Gresa et al., 2018). However, while there is evidence to suggest these systems may be effective, there are problems with overgeneralization in the field as researchers tend to implement a broad variety of VR technologies for an extraordinarily heterogeneous population. Therefore, the purpose of this systematic literature review is to uncover, analyze, and present the design characteristics of VR systems that have been designed as intervention or training tools for individuals with ASD. The following three research questions guide this inquiry:

RQ 1: How do designers of VR interventions for individuals with ASD characterize/define VR?

RQ 2: To what extent do VR systems described in the literature address the questions proposed by Parsons (2016), namely: (a) which technologies were used, (b) for whom, (c) in which contexts, (d) with what kinds of support, and (e) for what kinds of tasks/objectives?

RQ 3: How are the distinguishing characteristics of virtual learning environments, as outlined by Dalgarno and Lee (2010), instantiated in VR interventions designed for individuals with ASD?

2. Methods

A systematic review was conducted to approach these overarching aims (Davis et al., 2014) with the goal of providing reliable conclusions to better inform the field regarding identified issues (Moher et al., 2009). The Preferred Reporting Items for Systematic reviews and Meta-Analysis (PRISMA) standards were followed to provide methodological and reporting quality (Moher et al., 2009). The Problem, Interest, COntext approach (PICo) was used to inform the focus of this systematic review (Stern et al., 2014), a qualitative recasting of the established PICO framework for meta-analyses (Stern et al., 2014; Butler et al., 2016). Keyword and controlled vocabulary search strategies and search filters were established using the following PICo framework for Qualitative Studies (Butler et al., 2016):

(1) Population (P): Researchers of VR interventions for individuals with ASD
(2) Interest (I): Designs, definitions/operationalizations of VR training applications and interventions for the population.
(3) Context (Co): Research projects that use VR as a tool to deliver interventions to people with ASD.

To identify articles to be included for this review, the electronic databases Web of Science, PubMed, Scopus, IEEE

Xplore, and ERIC were searched. Google Scholar was also searched as a secondary tool to seek literature that may have been missed in the full systematic review of the electronic databases (Gusenbauer & Haddaway, 2020; Haddaway et al., 2015).

2.1. Protocol and registration

The protocol for this systematic literature was developed following PRISMA guidelines (Moher et al., 2009). The protocol was registered as per PRISMA guidelines and can be found on the Open Science Foundation at osf.io/5asyg.

2.2. Eligibility criteria

Manuscripts were considered to be eligible for inclusion based on the following criteria. Firstly, manuscripts had to be peer reviewed articles, published in academic journals, and in English. The decision to include only peer-reviewed journal articles (as opposed to "gray" literature such as conference proceedings, theses, and dissertations) was made so as to identify work of highest quality. Conference proceedings, "gray" literature, literature reviews, conceptual papers, patents, and citations were excluded. Only articles published after 1995 were included, as the first work concerning the use of virtual reality and autism was published in 1996 (Strickland, 1996b). Next, articles had to provide a description of a VR system specifically designed for individuals with ASD (i.e., a bespoke system). To be included in this literature review, the projects had to be specifically referred to as being 'virtual reality' or to have the technology's affordances and benefits described. Manuscripts that did not describe a VR system or that described VR systems not specifically designed for individuals with ASD (e.g., general, off-the shelf systems such as console video games, driving simulators, etc.), as were manuscripts that miscategorized their intervention as VR when it was something else (e.g., augmented reality, text-based virtual environments, etc.). Further, the VR system described had to have been used to deliver an intervention or training. Manuscripts that described VR systems that were used for diagnosis of ASD or for enjoyment or entertainment were excluded, as were those that evaluated feasibility and acceptance of technology but lacked an intervention/training component. In addition to this, evaluation or empirical research data on the VR system, virtual world, or virtual environment had to be presented. Manuscripts that only described design or provided proof-of-concept descriptions were excluded. Finally, the training or intervention had to include individuals with ASD as users. Studies that, for example, only reported on expert review or parent perceptions of a VR system were excluded.

2.3. Information sources

All searches were conducted in March, 2020. Databases searched for this systematic review were Web of Science, PubMed, Scopus, IEEE Xplore, ERIC, and Google Scholar. Web of Science is a subscription-based scientific indexing platform that provides comprehensive citation data across many disciplines. The Web of Science Core Collection is made up of six databases. PubMed is a database maintained by the National Center for Biotechnology Information and includes more than 30 million citations primarily related to life sciences and biomedical topics. Scopus is an abstract and citation database launched by Elsevier. Scopus includes book series, trade journals, and journals related to life sciences, social sciences, health sciences, and the physical sciences. IEEE Xplore is a digital library that provides access to over five million publications related to electrical engineering, computer science, and electronics. More than 20,000 new documents are added to the IEEE Xplore library every month. The ERIC Collection is an online library that was established in 1966. ERIC is currently sponsored by the Institute of Education Sciences by the United States Department of Education. It includes various types of publications including journal articles, books, conference papers, technical reports, dissertations, and more. The ERIC dataset includes over 1.5 million records which are largely available in Adobe PDF format. Google Scholar is a free search engine that indexes full text and metadata of the literature including peer-reviewed manuscripts, conference papers, dissertations, preprints, technical reports, patents, and other scholarly works. Google Scholar is estimated to include approximately 400 million documents in its index. Google Scholar was also searched as it has emerged as being the go-to academic search tool for many in the field due to its ease-of-use and convenience (Gusenbauer & Haddaway, 2020). However, while Google Scholar's immense dataset serves as a multidisciplinary collection of knowledge, it lacks many of the features required for conducting a systematic search such as the ability to specify tailored queries with high recall and precision. Therefore, this search engine was only used as a secondary tool to seek literature that may have been missed in the full systematic review of the electronic databases (Gusenbauer & Haddaway, 2020; Haddaway et al., 2015).

2.4. Search

An iterative approach was used to develop the search strategy. Cursory searches were conducted and initial results were reviewed to examine the nature of the returned literature. This strategy was refined over several iterations. Ultimately, the search terms used in this systematic review included variations of autism AND virtual reality and/or environments. In addition to using the PICo strategy for developing search queries, additional variations in terminology were adapted from other reviews of the literature in the field (Alcañiz et al., 2019; Brattan, 2019; Karami, 2020; Mesa-Gresa et al., 2018). We chose to include keywords such as 'virtual worlds' based upon published search strategies from other reviews of the literature (see Karami, 2020; Mesa-Gresa et al., 2018) and because of the broad conceptualizations of how VR is often conceived and defined with no consideration toward hardware and software perceptions in the field of autism research. An example query is provided in Table 1. See Appendix A for our full keyword strategy.

A search was conducted across all databases and search indexes stated above. A comprehensive list of search queries

Table 1. Unstructured database search query consisting of search terms and Boolean operators.

Term One	Condition	Term Two
(virtual reality) OR (virtual realit*) OR (virtual learning environment) OR virtual learning environment*) OR (virtual-reality) OR (virtual-realit*) OR (VR) OR (virtual environment) OR (virtual environment*) OR (virtual world) OR (virtual world*) OR (virtual-world) OR (virtual-world*) OR (collaborative virtual learning environment*) OR (3d virtual worlds) OR (3d virtual world*) OR (MUVE) OR (CAVE) OR (head-mounted display)	AND	(autism) OR (autism*) OR (autistic) OR (autis*) OR (asperger) OR (autism spectrum disorder) OR (asd) OR (Asperger Syndrome) OR (asperger's) OR (Asperger*) OR (Autistic Disorder) OR (Autistic)

across databases is provided in Appendix A. Filters and limits were applied based on the nature of the index and provided functionality (e.g., IEEE Xplore only goes back to 2005; see Table 2).

2.4.1. Search results reliability

An analysis was performed to assess reliability of search results. Six days after the initial search was conducted, the second author performed database searches using the same search strategy (queries, keywords, filters, etc.) across the databases to validate the number of returned results. Results suggested high agreement. In total, there was a difference of five records in comparison to the first author. Upon further analysis, these differences were found to be due to (1) new articles becoming available and (2) nuances across computing environments (e.g. cookies, browser version, other personalizations).

2.5. Study selection

First, a search was conducted and results were imported into RefWorks (http://refworks.proquest.com/). Results were compared to identify duplicates. A combination of automated searches (Exact Match, Close Match, and Legacy Close Match) and manual review was used. Identified duplicates were removed. Second, titles and abstracts of the remaining corpus were reviewed. Inclusion and exclusion criteria were applied. Third and finally, full text was reviewed and inclusion and exclusion criteria were applied. The final result was a corpus of 82 articles. The study selection process is illustrated in Figure 1.

2.5.1. Study selection inter-rater reliability

Screening was performed by the first author, with a subset of articles screened by a trained graduate student to establish inter-rater reliability. The trained graduate student applied inclusion and exclusion criteria to a 25% sample of the corpus of manuscripts after duplicates had been removed (n = 765; see Figure 1). Reliability was calculated by using the number of agreements between the observers and dividing by number of agreements plus disagreements. The coefficient was then calculated by multiplying that value by 100 to compute the percentage of agreement, resulting in an agreement estimate of 87.8%, suggesting high agreement.

2.6. Data collection process

We reviewed all publications associated with a given VR intervention/project so as to extract all relevant details across articles. Although Kitchenham (2004) warns against including multiple publications from the same dataset or research projects to avoid bias, this guideline refers to studies that focus specifically on empirical outcomes; however, our research questions were focused not on empirical findings but on design factors. Therefore, grouping articles that reported on the same project was necessary, as sometimes not all design details were reported in a single article and had to be extracted across multiple articles on the same project. Project IDs were created and corresponding articles were grouped with those IDs. IDs combined project name (if given) and the principal investigator's last name. In cases where a project did not have a stated name, a descriptive title was created (e.g. Lorenzo et al. IVRT). In cases where we were unable to determine if an article was reporting on the same VR system as another article by a similar author group, we followed Kitchenham's (2004) guidelines and contacted the authors to seek clarification, keeping projects separate if no response was received. The process of extracting relevant information on the system's design, hardware, software, participants, training goals, supports, etc., was facilitated using customized spreadsheets. A total of 49 projects were identified from the corpus of 82 included manuscripts (see Tables 3 and Tables 4).

2.7. Data items

Data extracted from each manuscript included:

- *Source and full reference*: An APA reference was generated and stored in a reference manager
- *Definition of virtual reality*: A summary of how authors describe/define VR; only included if authors explicitly

Table 2. Filters or limits applied to each index used in the literature review.

Database	Filters or Limits Applied
PubMed	Published between 1995–2020, English language, human subjects
Web of Science	Published between 1995–2020, English language, TOPIC
Scopus	Published between 1995–2020, English language, article format, published
IEEE Xplore	Published between 2005–2020, journals, and magazines
ERIC	Published between 1995–2020, peer-reviewed only
Google Scholar	Published between 1995–2020, exclude patents, exclude citations, not signed-in/incognito

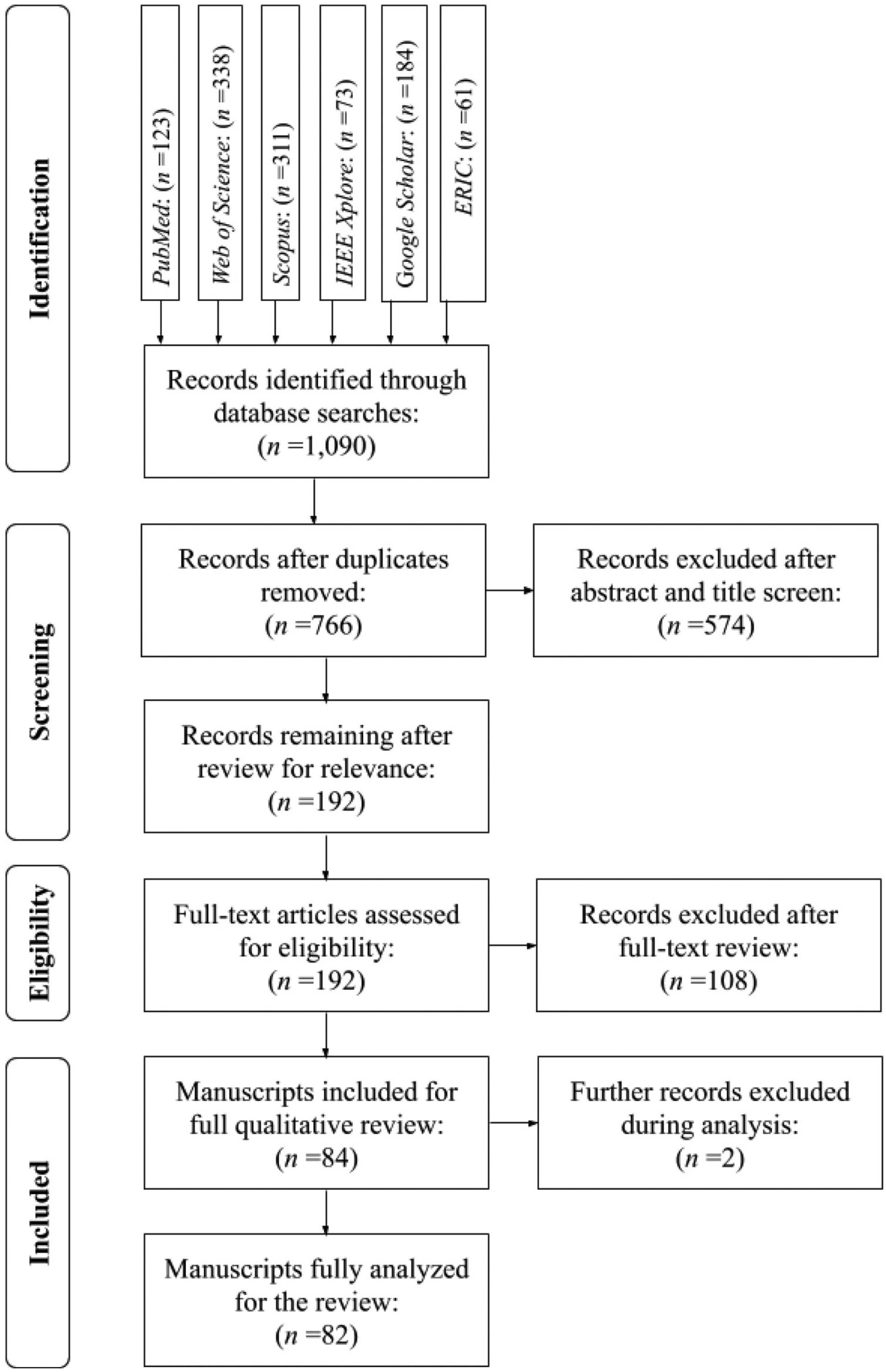

Figure 1. Flow diagram illustrating systematic search and selection process.

defined VR. A description of proposed benefits was not considered a definition and was not included.

- *Description of technologies*: The "which technologies" of the Parsons' (Parsons, 2016) framework. A summary of the technologies used in the VR system or intervention. This description included both hardware and software configurations if provided and included information about the number of users the system supported at once (e.g Single-user or Multi-user)
- *Target audience*: The "for whom" of the Parsons' (Parsons, 2016) framework. A summary of participants demographics and ASD diagnosis. Ages are categorized in categories, including (1) children (0–9 years old), (2) adolescents (10–19 years old), and (3) adults (20+ years

Table 3. Definitions of VR across projects/interventions.

VR System	VR Definition
VR Adaptive Driving System (Bian et al., 2013; Wade et al., 2016, Wade et al., 2017; Zhang et al., 2017)	Engaging visual medium often in the form of video games that can be used to create immersive, interactive, and realistic environments.
iSocial (J. Laffey et al., 2012; J. M. Laffey et al., 2014; M. Schmidt et al., 2014; Schmidt, 2014; Matthew Schmidt et al., 2012; Stichter et al., 2014; Wang et al., 2016, Wang et al., 2017)	Auditory and visual interactive technology which may represent a reduction of information from a real-world setting but also represents a full description of a setting without the need for imagined components.
Immersive VRET and Cognitive Behavioral Therapy System (Maskey et al., 2014, M. Maskey et al., 2019; Maskey et al., 2014, Maskey et al., 2019)	Computer-generated virtual images/scenes.
Fire and tornado safety system (Self et al., 2007)	Computer-generated, interactive, three-dimensional environment.
Immersive VR (Herrero & Lorenzo, 2020)	Where a user is immersed in a computer-generated world so that the point of view upgrades according to the position of the user. To provide greater realism and interaction.
IVRT research (Lorenzo et al., 2016)	A computer generated world, where users are entirely immersed and have the impression that they have "stepped inside" a synthetic world.
E-VISP (Babu et al., 2018)	A 3D computer generated virtual world that is capable of providing real-life imagery of the physical world.
Pronunciation VR platform (Chen et al., 2019)	Simulation of the real world based on computer graphics.
VR4VR (Bozgeyikli et al., 2017)	A model of reality where one can interact with and get information from ordinary human senses and can control the model using ordinary human actions.
VR Intervention (Ip et al., 2018; Yuan & Ip, 2018)	Immersive, computer generated world that can be created to simulate real-life situations.
Virtuoso-SVVR (Schmidt et al., 2019)	Three-dimensional, computer simulated environments that can be experienced by users with specialized electronic equipment. Promotes concepts of presence, telepresence, and spatial immersion.
Street Crossing Platform (Dixon et al., 2019)	Computer-based, multisensory, simulated environments that are navigated using different technologies.
Virtual Travel Training (Simões et al., 2018)	Artificial, 3D, computer-generated environments which the user can explore and interact with.
JobTIPS (Strickland et al., 2013)	A technology where users can practice context-based social and adaptive skills, facilitated in real time by an instructor, within computer generated environments.
Blood drawn exposure therapy (Meindl et al., 2019)	Technology that can realistically simulate a three-dimensional environment.
3D-SU system (Cheng et al., 2015)	A realistic simulated 3D world.
Virtual Reality Social Cognition Training (Didehbani et al., 2016; Kandalaft et al., 2013)	Computer-based simulation of reality in which visual representations, based in everyday life settings, are presented on a screen.
Interaction Training (Ke et al., 2015; Ke & Im, 2013)	Computer generated, three-dimensional representation of real-life environment.
Hand-in-Hand (Zhao et al., 2018)	Interactive and immersive simulated situations.
VR-CR (M. Wang & Reid, 2013)	Simulation of the real world using computer graphics.
VLSS (Volioti et al., 2016)	Three-dimensional computing environment in which users can be immersed and interact.

old). If the authors described participants in terms of necessary levels of support, that information was also included (e.g., "low functioning", Level 2).

- *Context of the study*: The "in which contexts" of the Parsons' (Parsons, 2016) framework. A description of both the physical context and the virtual context. The physical context is defined as where the VR intervention was administered (e.g., in a controlled university setting). The virtual context is defined as where the virtual activities took place (e.g., in a virtual replication of a shopping mall).
- *Supports*: The "with what kinds of support" of the Parsons' (Parsons, 2016) framework. Supports included the instructional, pedagogical, intervention, etc., supports and scaffolds of the VR intervention and training environment.
- *Tasks and/or objectives*: The "for what kinds of tasks or objectives" of the Parsons' (Parsons, 2016) framework. A description of the overarching task that was the instructional or learning focus of the VR system. A clinical target was also identified. Clinical targets were characterized using the same categories as used in Mesa-Gresa and colleagues' work (Mesa-Gresa et al., 2018).
- *System Description*: A summary of the overall VR system including a description of user interactions, goals, and supports. Used to provide context for identified design factors from the Dalgarno and Lee (2010) framework.
- *Design Factors*: Design factors that are evident in the VR system. Design factors are characterized using the characteristics of Dalgarno and Lee's elaborated model of learning in 3D virtual learning environments (2010). These unique characteristics relate to representational fidelity (realistic display of environment, smooth display of view changes and object motion, consistency of object behavior, user representation, spatial audio, kinesthetic and tactile force feedback) and learner interaction (embodied actions, embodied verbal and non-verbal communication, control of environment attributes and behavior, construction/scripting of objects and behaviors).
- *Design Factors Description*: A description of how the design factors (Dalgarno & Lee, 2010) are instantiated in the design of a VR system.

3. Results

The following section summarizes the results of this literature review.

3.1. Study selection results

Initial search across five indexes resulted in a total of 1,090 results. This pool of resources was culled to 766 articles after duplicates were removed. A total of 192 articles remained after a review of titles and abstracts was conducted for relevance. A full-text review was performed on these 192 articles by the first author and inclusion and exclusion criteria were applied. The outcome of this process was a final corpus of 84 articles that met the inclusion criteria. A secondary analysis was performed by the second author on these 84 articles, with further two articles excluded because they did not have an evaluation component or had been published as conference proceedings. These 82 articles were then categorized by project (as described above), resulting in a total of 49 records representing different interventions/projects. A diagram illustrating the search and selection process is provided in Figure 1.

RQ 1: How do designers of VR interventions for individuals with ASD characterize/define VR?

Analysis of articles associated with the 49 projects found that 22 projects (44.9%) provided explicit definitions of VR and 27 projects (55.1%) did not, as reported in Table 3.

Of the projects that did define virtual reality in their manuscripts, there were a range of characteristics described. For instance, ten (20.4%) defined VR as some kind of computer-generated environment, scene, or world. Eleven (22.4%) projects defined VR as providing an environment based on the real-world or providing a model of reality that is realistic and ecologically sound. Six projects (12.2%) stated that VR provides sensations of tele-presence including physical immersion or a psychological sense of feeling ‘there’ within a synthetic world. Nine projects (18.4%) stated that VR allows users to interact with the environment that is being presented including other users and objects within the virtual world. One project (2%) defined VR as being game-like. We do note that there was overlap in how researchers defined virtual reality in their work and that several projects fell within more than one categorization.

RQ 2: To what extent do VR systems described in the literature address the questions proposed by Parsons (2016)**, namely: (a) which technologies were used, (b) for whom, (c) in which contexts, (d) with what kinds of support, and (e) for what kinds of tasks/objectives?**

Articles associated with the 49 projects were reviewed and data associated with Parsons’ (Parsons, 2016) framework were extracted along the dimensions of (a) which technologies, (b) for whom, (c) in which contexts, (d) with what kinds of support, and (e) for what kinds of tasks/objectives. The results of this data extraction process are reported in Table 4.

3.1.1. Which technologies?

Clearly, a wide variety of VR technologies and interfaces are used to deliver interventions (see Figure 2). Thirty-two projects administered interventions on desktop-based interfaces that present virtual environments on a computer monitor and implement a combination of controller options. Five projects used CAVE systems where scenarios were projected onto a combination of screens that users could interact with through motion trackers, cameras, or other wearables. Eight projects used fully HMD where users perceive virtual experiences through wearable helmets and their gestures are captured through various trackers and controllers. Five projects delivered their interventions through mobile-based systems that present scenarios through videos and interactive worlds that can be perceived through lightweight HMD and controllers. Three projects used a projector-based system that allowed users to interact with the system through a Microsoft Kinect or a motion tracking device.

Varying human-computer interfaces are used to provide possibilities for user interaction and display of information with the different VR technologies illustrated in Figure 2. Desktop-based systems included the use of keyboards, computer mice, joysticks, haptic devices (e.g. a pressure sensitive Geomagic Touch Haptic Device), video game controllers, eye-gaze contingent devices, motion trackers, and driving interfaces. Gaze contingent systems (18.75% of desktop-based VR) and systems with some combination of keyboard/mouse or controller options were the most common (71.9% of desktop-based VR). CAVE-based interfaces utilized a variety of configurations including: 6-walled CAVE, full 360-degree CAVE, 4-walled CAVE, a half CAVE, and an L-shaped CAVE. All five mobile-based VR systems were presented using lightweight mobile HMD including Google Cardboard, Google Daydream, and the Tzumi Dream Vision. Three of the mobile-based VR projects (60%) presented digital worlds that users could interact with using various input methods. Two of the mobile-based VR projects (40%) provided users with 360-degree video-based scenarios. Of the eight fully immersive HMD-based VR systems, five were presented in an Oculus Rift (62.5%). The other three fully immersive HMD used the ProVison, I-Glasses, and the Z800 3DVisor, respectively.

3.1.2. For whom?

The projects and interventions reviewed were designed for a wide range of participants with ASD, with demographics that vary considerably in age and diagnostic measures (see Table 4). Reporting of necessary levels of support for participants is inconsistent, and few articles identify participant comorbidities. Age ranges of participants are the most commonly reported demographic item. The majority of research in this field has been conducted with children (aged 0–9) and adolescents (aged 10–19). Interventions designed for adults (20+) are less common (Figure 3). These findings are in agreement with other published reviews (Lal Bozgeyikli et al., 2018; Mesa-Gresa et al., 2018; Parsons, 2016).

3.1.3. In which contexts?

Reporting of the physical contexts in which projects/interventions were implemented was inconsistent, with the majority of projects (76.5%) failing to include this information. From the

Table 4. *Description of VR projects/interventions for individuals with ASD as categorized using the schema suggested by* Parsons (2016).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
VR Adaptive Driving System (Wade et al., 2016; Wade et al., 2017; Zhang et al., 2017; Bian et al., 2019)	Single-User, desktop-based driving interface that used Logitech G27 (wheel) controller and various addons (eye tracking, eeg, etc) to provide adaptive responses by the system.	Adolescents between 13–18; Autism diagnosis based on SRS, SCQ, IQ	**Physical context**: Not described **Virtual context**: Nonfictional. A replication of a city in the U.S.A.	● Contextualized corrective feedback ● Just-in-time corrective feedback ● Token economy	**Program goals**: Driving skills **Clinical target**: Daily living skills
iSocial (Wang et al., 2018; Schmidt, 2014; J. M. Laffey et al., 2014; J. Laffey et al., 2012; Stichter et al., 2014; Wang et al., 2016; Wang et al., 2017; M. Schmidt et al., 2014; Matthew Schmidt et al., 2012)	Multi-User, desktop-based VR built using Java-based OpenWonderland virtual worlds toolkit to deliver online training at-a-distance.	Youth between 11–14; High-functioning autism or Aspergers based on ADI-R, ADOS	**Physical context**: School setting **Virtual context**: Fictional. Five fantasy environments, including a boat, restaurant, castle, etc.	● Token economy ● "Social orthotics" ● Visual schedules ● Online guide	**Program goals**: Deliver SCI-A curriculum **Clinical target**: Social skills
Gaze sensitive Adaptive Response Technology (Lahiri et al., 2015; Lahiri et al., 2011; Lahiri et al., 2011)	Single-User, Gaze contingent Desktop-based VR built in Vizard from Worldviz Llc.	Youth between 13–18; Autism diagnosis based on PPVT, SRS, SCQ, ADOS-G, ADRI-R	**Physical context**: Not described **Virtual context**: Fictional. Scenarios were based on diverse topics and locations of interest to teenagers. For example, one scenario involved a scene at the beach.	● Adaptive difficulty	**Program goals**: Social Interaction training **Clinical target**: Social skills
Immersive VRET and Cognitive Behavioral Therapy System (Maskey et al., 2014; Maskey, McConachie, et al., 2019; Maskey, Rodgers, Grahame, et al., 2019; Maskey, Rodgers, Ingham, et al., 2019)	Single-User, CAVE-based system called the 'Blue Room' where scenes are projected onto a 360 degree screened room. Scenes are controlled by a therapist with an iPad.	Youth between 8–14; Autism diagnosis based on: DSM-IV or ICD-10 criteria from NHS; No comorbid learning disabilities	**Physical context**: University setting **Virtual context**: Nonfictional. Various scenes based on individual user's phobias including: Street scene with open land. Dogs of different sizes would appear and run around; Inside a virtual car that would drive through the streets; Entrance to a school from a participant's life; Dimly lit corridor; Replica of a local sports center; Scenarios of fire drills; Inside a house during a storm	● Individual treatments ● Gradual exposure ● Cognitive Behavioral Techniques	**Program goals**: Treatment of phobias **Clinical target**: Phobia or fear
Fire and tornado safety system (Self et al., 2007)	Single-User, Desktop-based VR system made with EON Professional 5.0; 3DS Max 6.0 software	Youth between 6 to 12 years	**Physical context**: School setting **Virtual context**: Fictional. Virtual buildings unfamiliar to participants	● Navigational scaffolds ● Visual cues and prompting ● Evolving complexities	**Program goals**: Teaching safety skills related to fire and tornado events **Clinical target**: Daily living skills
AViSSS (Ehrlich & Miller, 2009)	Single-User, Desktop-based VR system where users click on multiple choice options to progress through scenarios. Created in OGRE 3D Rendering Software	Adolescents	**Physical context**: Not described **Virtual context**: Fictional. Hallways, restrooms, buses, and cafeterias unfamiliar to the participants	● Ability to fail and replay scenarios ● Corrective system	**Program goals**: Teaching social skills **Clinical target**: Social skills
Bob's Fish Shop (Rosenfield et al., 2019)	Single-User, HMD-based-VR in Oculus Rift made in Unity	One 6 year old adolescent with ASD	**Physical context**: Not described **Virtual context**: Fictional. Cartoon pet store	● User progress tracking ● Gaze tracking and analysis	**Program goals**: Social skills development **Clinical target**: Social skills
Virtual Joystick (Kim et al., 2015)	Single-User, Desktop-based VR with a joystick made in Game Studio A6 rendering engine	Youth between 8–16; High Functioning diagnosis based on: IQ, SCQ, ASSQ, SRS, MASC, BASC, RME;	**Physical context**: Not described **Virtual context**: Fictional. Living room unfamiliar to the participants	● Increasing emotional intensity levels on avatars	**Program goals**: Examine social motivation and emotion perception **Clinical target**: Emotional Skills

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
CicerOn VR: Virtual Speech Coach (Rojo et al., 2019)	Single-User, Mobile-based-VR in Samsung Gear HMD with a controller made in Unity 3D	Individuals with Asperger's Syndrome	**Physical context**: Not described **Virtual context**: Fictional. Locations from around the world	● Gamified ● Gradual exposure ● Formative assessment through speech recognition	**Program goals**: Development of public speaking skills and addressing phobia related to talking in front of others **Clinical target**: Phobia or fear
Eye gaze VR (Grynszpan et al., 2019)	Single-User, Gaze contingent Desktop-based VR	Young adults with an average age of 24.06; Diagnosis based on Psychiatrist confirmed diagnosis using the DSM-IV R criteria	**Physical context**: Not described **Virtual context**: Fictional. Two twins would appear on a screen	Not reported	**Program goals**: Investigate attentional focus abilities **Clinical target**: Attention
IVR (Herrero & Lorenzo, 2020)	Single-User, HMD-based-VR in Oculus Rift made in Unity 3D	Youth aged between 8 to 15; Autism diagnosis; Level 1 and Level 2 of DSM-V	**Physical context**: Not described **Virtual context**: Fictional. Generic virtual school and garden	● Reduction of stimuli that could be distracting ● Simplified control system	**Program goals**: Train the emotional and social skills of students **Clinical target**: Emotional skills
CRETA (Zhang et al., 2020)	Multi-User, Desktop-based VR	Youth with an average age of 13.39; Diagnosis based on: SRS, SCQ, ADOS, IQ	**Physical context**: Not described **Virtual context**: Fictional. Problem solving games	● Adaptive system that responds to how a user is communicating	**Program goals**: Assessing Social Communication and Collaboration **Clinical target**: Communication ability
Facial Recognition VR (Bekele et al., 2014; Bekele et al., 2012; Bekele et al., 2013)	Single-User, Gaze Contingent Desktop-based VR made in Unity 3D	Youth aged between 13–17; Below risk range High functioning diagnosis based on: SRS, SCQ, ADOS-6, ADOS-CSS, IQ;	**Physical context**: Not described **Virtual context**: Fictional. Virtual characters displayed on a screen	Not reported	**Program goals**: Enhancing Facial Affect Recognition **Clinical target**: Emotional skills

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
VR-JIT (Smith et al., 2015; Smith et al., 2014; Smith et al., 2020)	Single-User, Desktop-based VR	Teenagers and adults between 16 to 31; High Functioning diagnosis based on SRS	**Physical context**: Not described **Virtual context**: Fictional. Virtual character representing a human resources manager in a large department store	● Repetitive simulated job interviews based on hierarchical learning ● Algorithm based on customizable features that adapts to learner needs ● Non-branching design that has over 2000 different simulations ● Displaying scores based on performance ● Difficulty levels where the interviewer becomes more agitated, hostile, or will even ask illegal questions	**Program goals**: Interviewing skills **Clinical target**: Daily living skills
IVRT research (Lorenzo et al., 2016)	Single-User, L-shaped CAVE-based and Desktop-based VR designed in Vizard from Worldviz Llc	Youth aged between 7–12	**Physical context**: Not described **Virtual context**: Fictional. Party and a classroom	● Adaptive system that responds to the actions of users in the environment	**Program goals**: Improve emotional skills **Clinical target**: Emotional skills
Virtual Dolphinarium (Cai et al., 2013; Lu et al., Lu)	Single-User, Projector-based with Microsoft Kinect	Youth aged between 6–17; Mild to severe diagnosis based on; TONI3, NIQ, GARS	**Physical context**: Not described **Virtual context**: Fictional. Next to a pool/virtual dolphin lagoon where users are able to interact with pink dolphins. The environment also includes underwater scenes where the dolphins can swim and behave naturalistically.	● Mirroring of psychomotor skills from in-game avatars ● Gamified ● Experiential learning methods	**Program goals**: To teach nonverbal communication through gesturing **Clinical target**: Communication ability
Haptic-Gripper Virtual Reality System (Zhao et al., 2018)	Single-User, desktop-based system that uses a haptic grip attachment that is made by augmenting a commercial haptic device (Geomagic Touch Haptic Device) with a 3D-printed gripper embedded with Force-Sensing Resistors	Youth aged between 8–12; Diagnosis based on: ADOS, SB-5, SRS;	**Physical context**: Not described **Virtual context**: Fictional. Virtual tasks and activities including Letter Tasks and curved Path Tasks	● Adaptive haptic, audible, and visual feedback	**Program goals**: Address motor skill deficits **Clinical target**: Physical activity
AS System (Kuriakose & Lahiri, 2017; Kuriakose & Lahiri, 2015)	Single-User, Desktop-based VR Designed in Vizard from Worldviz Llc	Youth aged between 10–16; Above Average IQ diagnosis based on: SRS, SCQ, SCAC;	**Physical context**: Not described **Virtual context**: Fictional. Social stores in relevant social situations such as a classroom, park, hotel, and etc.	● Tracks anxiety measures of individual users	**Program goals**: Social Communication Skills **Clinical target**: Social skills
E-VISP (Babu et al., 2018)	Single-User, Gaze contingent desktop-based VR Designed in Vizard from Worldviz Llc	Youth aged between 10–19; Clinical range diagnosis based on: SCAS, SRS, SCQ;	**Physical context**: Not described **Virtual context**: Fictional. Social contexts taking place in scenarios including: Birthday party and marriage party, dinner, classroom, restaurant, movie theater, and sporting events	● Eye tracking technology that can use gaze-based biomarkers to provide quantitative estimates of one's anxiety	**Program goals**: Social Communication **Clinical target**: Social skills

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
Immersive VR System (Halabi et al., 2017; Halabi et al., 2017)	Single-User, four walled CAVE-based, HMD-based in Oculus Rift, and Desktop-based VR	Youth aged between 4–6;	**Physical context**: Not described **Virtual context**: Fictional. On the grounds of a school and inside of a classroom	● Roleplay pedagogy to embody users in the task ● Auto-navigation through the environment	**Program goals**: Improve Communication Skills **Clinical target**: Communication ability
Pronunciation VR platform (Chen et al., 2019)	Single-User, Gaze contingent Desktop-based VR	Youth with an average age of 6.63; Low functioning diagnosis based on: GARS-2, CARS;	**Physical context**: Not described **Virtual context**: Fictional. A 3D virtual tutor presented as various models of their face, lips, tongue, jaw, and nasopharyngeal wall. The model would animate and change in order to generate realistic pronunciation models.	● Modeling of skills	**Program goals**: Word pronunciation training **Clinical target**: Communication ability
AS Interactive (Parsons et al., 2005; Parsons et al., 2006; Rutten et al., 2003; Mitchell et al., 2007; Parsons et al., 2004; Parsons, 2005)	Single-User, Desktop-based VR system controlled with a joystick and a mouse that was designed in Superscape Virtual Reality Toolkit	Youth aged between of 13–18; Diagnosis based on: FSIQ, WASI	**Physical context**: Not described **Virtual context**: Fictional. Within a social cafe´ and on a bus	● Scaffolding through various levels with different complexities ● Teacher-controlled pause feature to provide opportunities for communication with the users of the system ● Visual and verbal feedback provided to users on their performance	**Program goals**: Social Skills and Social Conventions Development **Clinical target**: Social skills
VR4VR (Bozgeyikli et al., 2017)	Single-User, VR220 HMD-based VR system made in Unity	College aged; High Functioning (Rutten et al., 2003)	**Physical context**: Not described **Virtual context**: Fictional. Several virtual environments in which the skill modules take place such as warehouse, grocery store, outdoor parking lot, office space, and street.	● Tutorial level as part of each virtual scenario ● System prompts provided to the user throughout ● Evolving complexities such as the addition of system distractors	**Program goals**: Vocational Rehabilitation **Clinical target**: Daily living skills
Street-crossing environment (Josman et al., 2008)	Single-User, Desktop-based VR made in f Superscape's 3D Webmaster	Youth aged between 8–16; Moderate to severe diagnosis	**Physical context**: Not described **Virtual context**: Fictional. Four-lane divided street with crosswalks	● Nine levels of evolving complexities and challenge ● Safe repeatable levels	**Program goals**: Street crossing skills **Clinical target**: Daily living skills
VR-Tangible Interaction System (Jung et al., 2006; Jung et al., 2006)	Single-User, Projector-based system with physical devices (e.g. a stick, a rotation board, a trampoline)	Youth aged between 5–6 Diagnosis based on: DSM-IV criteria	**Physical context**: Not described **Virtual context**: Fictional. Breaking virtual balloons with a real stick, food appearing on a screen, facial expressions appear on the screen	● Therapist controlled levels ● Visual and auditory responses are provided to give feedback ● Five phases that participants gradually go through	**Program goals**: Integrate sensory and motor experiences **Clinical target**: Physical activity

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
Emotional and social adaptationVR Intervention (Ip et al., 2018; Yuan & Ip, 2018)	Single-User, Half CAVE-based made in MiddleVR for Unity3D	Youth with an average age of 9.03	**Physical context**: Not described **Virtual context**: Fictional. Four seasons simulation, a home scene to practice morning routines, taking a bus, engaging in a classroom, a store, and a playground	● Game-based learning	**Program goals**: Enhance emotional and social adaptation **Clinical target**: Social skills
Block Challenge (Parsons, 2015)	Multi-User, Desktop-based VR made in DEMON	Youth aged between 10–13; High Functioning Diagnosis based on: SCQ;	**Physical context**: School setting **Virtual context**: Fictional. A virtual interface with a digital facilitator and different colored blocks that are used to solve puzzles	● Support agent ● In-person facilitator ● Various levels of difficulty	**Program goals**: Supporting communicative perspective-taking skills **Clinical target**: Communication ability
Virtuoso-SVVR (Schmidt et al., 2019)	Single-User, Mobile-based Spherical video-based virtual reality in Google Cardboard and Daydream HMD made in Unity	Adults aged between: 22–34; Diagnosis based on: PPVT, SRS, BRIEF	**Physical context**: University setting **Virtual context**: Nonfiction. Video scenarios taking place on a university campus and shuttle bus	● Video modeling ● Chunked content that is short and digestible ● Narration that explains the instruction	**Program goals**: Public transportation training **Clinical target**: Daily living skills
Street Crossing Platform (Dixon et al., 2019)	Single-User, Spherical video-based virtual reality in Oculus Rift ran in STEAM VR	Youth aged between 4–10; Average to High functioning diagnosis based on: PDDBI;	**Physical context**: Autism center setting **Virtual context**: Nonfictional. 360 degree videos of traffic patterns taking place in their local community	No reported	**Program goals**: Street crossing skills **Clinical target**: Daily living skills
Modified Virtual Errands Task (Rajendran et al., 2011)	Single-User, Desktop-based VR made in Superscape 3D Webmaster and run using Superscape Visualizer	Youth aged between: 11–17; High Functioning Diagnosis based on: IQ, WASI, VSIQ, VIQ, PIQ BADS	**Physical context**: Not described **Virtual context**: Fictional. An actual university building consisting of three floors that are connected by stairwells	● Tasks varied in complexities and required more steps to complete them as participants progressed through the intervention	**Program goals**: Multi-tasking evaluation while conducting various errands **Clinical target**: Daily living skills
Virtual Mall (Trepagnier et al., 2005)	Single-User, Desktop-based VR controlled with a joystick	Adults aged between: 19–27; Ability to think out loud	**Physical context**: Not described **Virtual context**: Fictional. Virtual mall	Not reported	**Program goals**: Navigating a mall and performing socially appropriate behaviors **Clinical target**: Social skills
Virtual Conversation Partner (Trepagnier et al., 2005; Trepagnier et al., 2011)	Single-User, Desktop-based VR	Aged between 16–30; Diagnosis based on: WASI	**Physical context**: Not described **Virtual context**: Fictional. Prerecorded virtual character that responses to dialog options	● Point system to provide a score and insight into the performance of users ● A help button which includes assistance features	**Program goals**: Conversational skills development **Clinical target**: Communication ability

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
Virtual Travel Training (Simões et al., 2018)	Single-User, HMD-based VR in Oculus Rift with gamepad controller	Young adults with average age of 18.9; Low to mild intellectual disability	**Physical context**: Autism center setting **Virtual context**: Fictional. In a virtual city that adapts to user's biofeedback and within public busses	• Difficulty levels of varying complexities • Scoring system • Adaptive biofeedback system	**Program goals**: Taking a bus to reach specified destinations **Clinical target**: Daily living skills
JobTIPS (Strickland et al., 2013)	Multi-User, Desktop-based VR through the VenuGen4 virtual reality platform	Young adults with an average age: 18.21; High Functioning Diagnosis based on: SRS	**Physical context**: Not described **Virtual context**: Fictional. In a realistic office space	• Video models • Visual supports • Clinician feedback in-system • Concrete explanations	**Program goals**: Interviewing skills **Clinical target**: Daily living skills
Crossing the Street (Strickland, 1997)	Single-User, HMD-based VR that uses a ProVision 100 fully integrated VR system by Division	Youth aged between 7–9; minimal vocabulary	**Physical context**: Not described **Virtual context**: Fictional. Simplified street scene with a sidewalk and textured buildings	• Continually modified for each individual between sessions • Reduction of in-world distractions	**Program goals**: Street safety **Clinical target**: Daily living skills
Floreo PSM (Parish-Morris et al., 2018)	Single-User, Mobile-based VR lightweight HMD	Users aged between 12–37; Diagnosis based on: WASI, SCQ	**Physical context**: Autism center setting **Virtual context**: Fictional. Throughout a virtual community	• Therapist can control officer responses to be adaptive • System is monitored by a therapist who provides instant feedback	**Program goals**: Police interaction skills **Clinical target**: Daily living skills
Blood drawn exposure therapy (Meindl et al., 2019)	Single-User, Mobile-based Spherical video-based virtual reality system with Tzumi Dream Vision HMD and an Apple pencil used to simulate a needle	One 26 year old participant with ASD	**Physical context**: Home setting and doctor's office setting **Virtual context**: Fictional. Blood draw video	• Gradual exposure • Safe comfortable administration settings	**Program goals**: Reducing phobia of having blood drawn **Clinical target**: Phobia or fear
3D Empathy System (Cheng et al., 2010)	Single-User, Desktop-based VR made in 3D Max, Virtools, and Poser.	Youth aged between: 8–10; Diagnosis based on: FSIQ, PIQ, VIQ, WASI	**Physical context**: Not described **Virtual context**: Fictional. A restaurant	• Simplified language • Virtual teacher or online guide would prompt questions	**Program goals**: Promote empathy **Clinical target**: Emotional skills
3D-SU system (Cheng et al., 2015)	Single-User, HMD-based VR in Model: I-Glasses PC 3D Pro	Youth aged between 10–13; Diagnosis based on: WASI, VIQ, PIQ, FSIQ	**Physical context**: Not described **Virtual context**: Fictional. A virtual bus stop and a classroom	• Social modeling • Awards system • Auditory feedback system	**Program goals**: Social understanding and skills development **Clinical target**: Social skills
Public Speaking Intervention (Jarrold et al., 2013)	Single-User, HMD-based VT with eMagin Z800 3DVisor made in Vizard from Worldviz Llc.	Youth aged between: 8–16; Diagnosis based on: WASI, SCQ, ASSQ, SRS; High functioning and low functioning comparison groups	**Physical context**: Not described **Virtual context**: Fictional. Classroom	• In-person guide who acted as a teacher in the virtual classroom • Visual cues • Difficulty levels	**Program goals**: Public Speaking Skills **Clinical target**: Daily living skills

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
Virtual Reality Social Cognition Training (Kandalaft et al., 2013; Didehbani et al., 2016)	Multi-User, Desktop-based VR in Second Life	Youth aged between 7–26; High Functioning diagnosis based on: ADOS	**Physical context**: Not described **Virtual context**: Fictional. An office building, a pool hall, a fast food restaurant, a technology store, an apartment, a coffee house, an outlet store, a school, a campground, and a central park	• Online guide that facilitated instruction	**Program goals**: Social Cognition Skills **Clinical target**: Social skills
Social Interaction Training (Ke & Im, 2013; Ke et al., 2015)	Multi-User, Desktop-based VR in Second Life	Youth aged between 9–10; HFASD or Asperger Syndrome diagnosis based on existing medical or educational records	**Physical context**: Home setting, School setting, and Parent's office setting **Virtual context**: Fictional. Birthday party and a cafe	• Online facilitator	**Program goals**: Social Interaction Training **Clinical target**: Social skills
Hand-in-Hand (Zhao et al., 2018)	Multi-User, Desktop-based VR with LeapMotion controller made in Unity	Youth with average age 12.38 and 12.60; Diagnosis based on; SRS, SCQ;	**Physical context**: Not described **Virtual context**: Fictional. Various collaborative games	• Score system • System feedback on performance	**Program goals**: Promote communication and collaboration skills **Clinical target**: Social skills
Eye-gaze system (Grynszpan et al., 2012)	Single-User, Eye Contingent Desktop-based VR	Adults with average age 20.19; High Functioning diagnosis based on: WAIS, DSM IV criteria	**Physical context**: Not described **Virtual context**: Fictional. Virtual characters expression emotion while talking	• Intonation was reduced to the minimum by using synthesized speech • Real-time feedback was provided about the gaze of participants as they used the system	**Program goals**: Self-Monitoring of Gaze **Clinical target**: Social skills
Pico's Adventure (Crowell et al., 2019)	Multi-User, Projector-based VR with Microsoft Kinect	Youth with average age of 5.69; Diagnosis based on: ADOS, ADI-R, WISC-IV >70	**Physical context**: Not described **Virtual context**: Fictional. Games	• Introduction phase • Game elements and reward system	**Program goals**: Collaboration Skills **Clinical target**: Social skills
Decoding Social Interactions (Jacques et al., 2018)	Single-User, 6 wall CAVE-based VR	Adults with typical intelligence	**Physical context**: Not described **Virtual context**: Fictional. Various social contexts such as a party, restaurant, bus stop, and a bar	• Virtual coach	**Program goals**: Decoding social interaction **Clinical target**: Social skills
VR-CR (Wang & Reid, 2013)	Single-User, Desktop-based VR Motion-capture technology was incorporated using a tracking webcam	Youth aged between 6–8; Diagnosis based on: CARS, PDD-NOS	**Physical context**: Home setting **Virtual context**: Fictional. Within a variety of locations relevant to the objects being assessed for contextual processing including a kitchen and bathroom	Not reported	**Program goals**: Improve contextual processing of objects **Clinical target**: Daily living skills

(*Continued*)

Table 4. (Continued).

Project and References	Which technologies?	For whom?	In which contexts?	What kinds of support?	For what kinds of tasks/objectives?
VLSS (Volioti et al., 2016)	Single-User, Desktop-based VR made in Open Simulator	Designed for youth with ASD between ages of 9–17 years	**Physical context**: Not described **Virtual context**: Fictional. School	• Wide, open, comfortable VR spaces to prevent issues with control and functionality which could impact cognitive load • Distractors from the real-world have been removed • Audible and visual feedback • Stable voice from virtual instructor	**Program goals**: Social communication skills **Clinical target**: Communication ability
VESIP (Russo-Ponsaran et al., 2018)	Single-User, Desktop-based VR	Youth aged between 8–12; Verbal and diagnosed based on:, SCQ, IQ above 80	**Physical context**: University setting and School setting **Virtual context**: Fictional. Watching avatars behave in a school setting	• Virtual helper agent • Customized to the user	**Program goals**: Social Information Processing **Clinical target**: Social skills

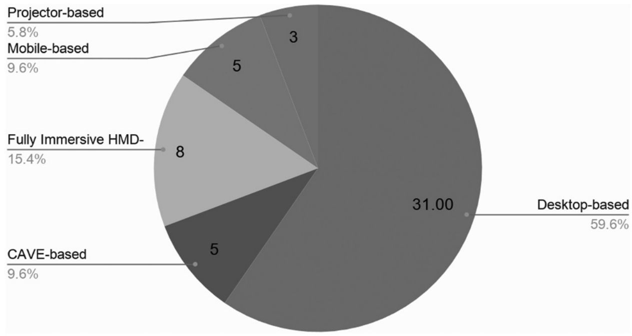

Figure 2. Overview of VR technologies used across 49 identified projects/interventions.

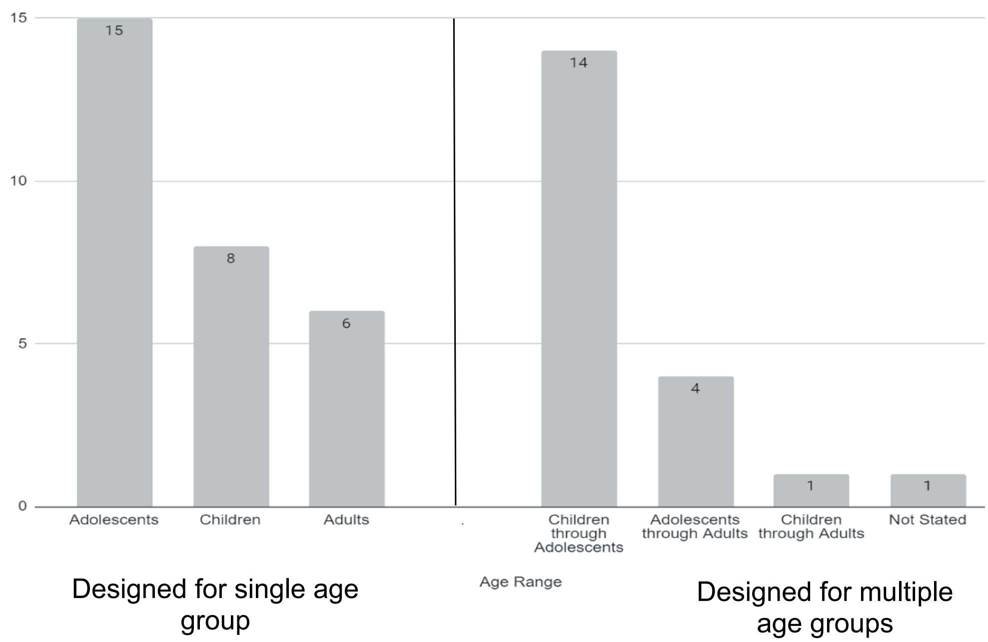

Figure 3. Participant age ranges across identified VR projects/interventions.

12 projects that did report this information, it is evident that physical contexts varied considerably, as shown in Figure 4, and that few projects were situated outside controlled settings.

Of the virtual contexts identified, the majority were based on fantasy or fictional environments (94.1%), with a minority situated in real-world settings (5.91%). Fictional settings were defined as virtual environments that, while sometimes realistic, were not based on settings from the real-world. Examples include: birthday parties, schools, shopping centers, cafeterias, and inside of a bus. Nonfictional settings were defined as virtual environments that were based on real-world settings, often from the lives of the target participants. For example, Schmidt et al., (2019) created a spherical video-based virtual reality training application that included high-definition footage from actual settings that adults with ASD typically encountered in their day program.

3.1.4. With what kinds of support?

Reporting of instructional supports and scaffolds in the literature is inconsistent. Many projects do not report, but rather imply the instructional supports that is provided by the VR system. When supports are reported, they tend to be closely aligned with the system design and are therefore highly contextualized. Therefore, summarizing and synthesizing supports is challenging as there is little consistency across reporting or implementation. However, broad descriptions of these supports are implied. For example, several VR systems are reported to provide users with adaptive system response to individualize the task to the unique needs of the individual (Parish-Morris et al., 2018; Lorenzo et al., 2016; Simões et al., 2018; Zhao et al., 2018). How this support is provided is not always detailed and system configurations impact how supports are provided to users. In some cases bio-feedback and user metrics are collected

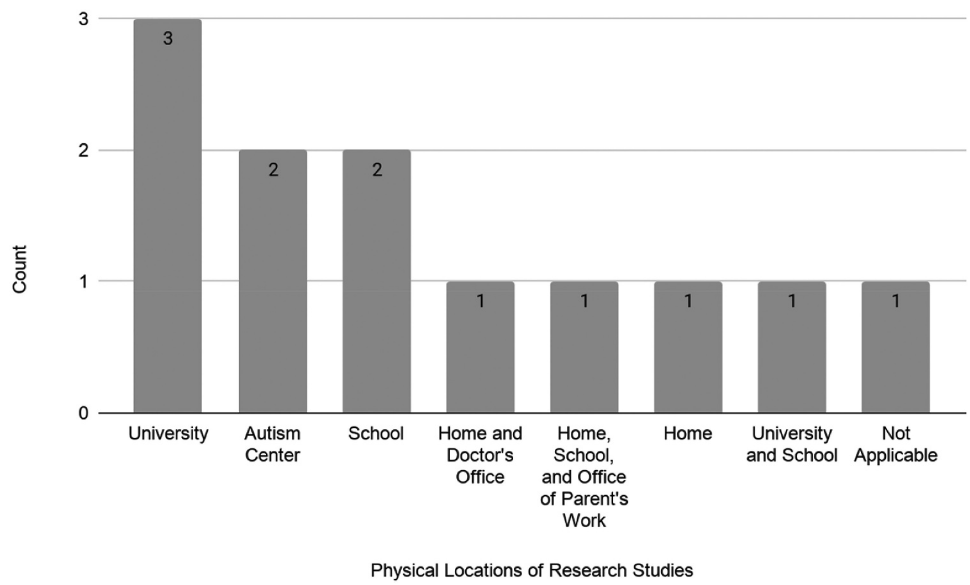

Figure 4. Breakdown of Physical Contexts Used in the Literature.

(Babu et al., 2018; Simões et al., 2018) through external peripherals that tie into the software of the VR system to provide dynamic experiences. In other cases, the actions of users, such as their repeated failures, impact how the system responds and adapts (Lorenzo et al., 2016). These findings align with other reviews that state that researchers of VR experiences need to do a better job with reporting on pedagogical decisions (Fowler, 2015), including adaptive supports (Zahabi & Abdul Razak, 2020).

3.1.5. For what kinds of tasks/objectives?

Tasks and objectives were characterized using the same categories as reported in Mesa-Gresa et al. (2018): social skills, emotional skills, daily living skills, communication ability, attention, physical activity, and phobia or fear. The majority of projects/interventions identified target the development of social skills (34.7%) and daily living skills (28.6%). Seven studies (14.3%) were designed to target communication skills development. Five studies (10.2%) focused on emotional skill development. Three studies (6.1%) focused on the creation of systems to help with the treatment of phobias or fear. Two studies (4.1%) focused on the training of physical skills. One study (2%) focused on attention skills. Figure 5 shows the full breakdown of studies that focused on each of the clinical targets. These findings are largely in agreement with those reported in Mesa-Gresa and colleagues' work, with some key

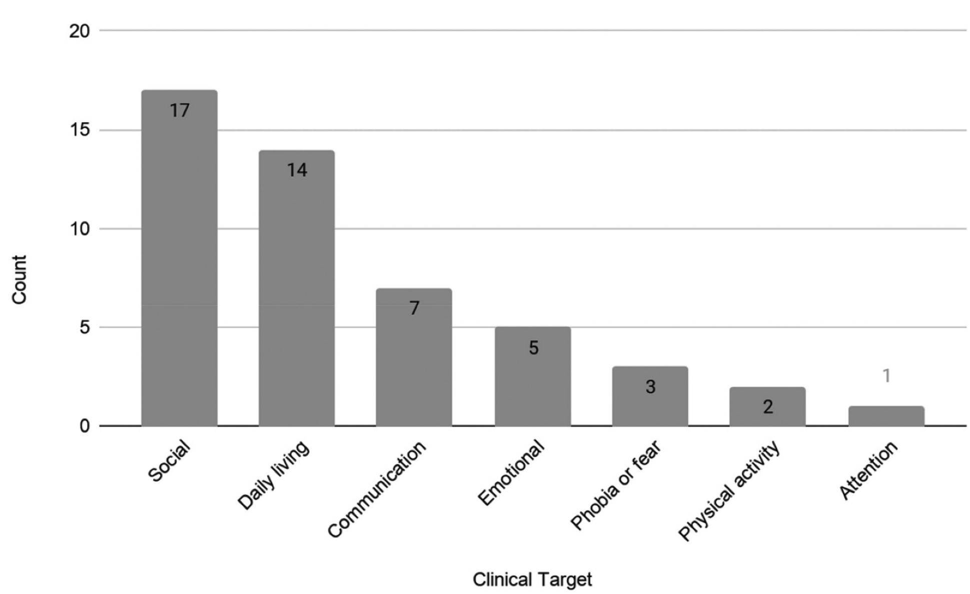

Figure 5. Clinical targets of Training Activities.

differences. Fewer projects in our work focused on emotional skills, for example.

RQ 3: How are the distinguishing characteristics of virtual learning environments, as outlined by Dalgarno and Lee (2010)**, instantiated in VR interventions designed for individuals with ASD?**

Articles associated with the 49 projects were reviewed and data extracted according to Dalgarno and Lee (2010) elaborated model of learning in 3D virtual learning environments. (Dalgarno & Lee, 2010). Specifically, projects were categorized along the dimensions of unique characteristics related to representational fidelity (realistic display of environment, smooth display of view changes and object motion, consistency of object behavior, user representation, spatial audio, kinesthetic and tactile force feedback) and learner interaction (embodied actions, embodied verbal and non-verbal communication, control of environment attributes and behavior, construction/scripting of objects and behaviors). Findings suggest designers of VR environments sought to exploit a number of distinguishing characteristics of virtual learning environments to promote learning within their training programs. The manner in which these design factors were instantiated varied across projects and system architecture. Findings are reported in Table 5.

Designing for a realistic environment was the most commonly cited consideration in the literature and was used in 33 of the projects (67.3%). The second most frequent design factor was seen in 31 of the projects in which action is embodied through a virtual avatar (63.3%). Designing for consistent object behaviors was seen in 15 of the projects (30.6%). The ability for users to embody verbal and non-verbal communication through an avatar was seen in 15 of the projects (30.6%). A realistic user representation was seen in four (8.2%) of the projects. Kinesthetic and tactile force feedback was only utilized in two (4.1%) projects. Both the use of spatial audio and a smooth display of view changes and object motion was seen in only 1 project (2%). A full breakdown of these Dalgarno and Lee design factors and how they are instantiated is provided in Figure 6.

4. Discussion

Three questions guided this systematic review: (1) How do designers of VR interventions for individuals with ASD characterize/define VR? (2) To what extent do VR systems described in the literature address the questions proposed by Parsons (2016), namely: (a) which technologies were used, (b) for whom, (c) in which contexts, (d) with what kinds of support, and (e) for what kinds of tasks/objectives? And (3) How are the distinguishing characteristics of virtual learning environments, as outlined by Dalgarno and Lee (2010), instantiated in VR interventions designed for individuals with ASD? To address these questions, 84 manuscripts were selected and analyzed. We discuss our findings in the following sections.

4.1. *Lack of consensus around what constitutes VR*

A review of VR definitions suggests there is no established and field-recognized operationalization of what defines VR. Many characterizations are presented with some authors claiming VR is a representation of the real-world, others stating VR is any form of computer-generated imagery, others comparing VR to video games, and some stating that VR requires sensations of telepresence. This finding is problematic because any discussions of affordances of VR necessarily are precluded by a base understanding of the technology itself. Further confusion stems from the fact that 55.1% of the projects returned in this literature review do not define the term at all, although many cite literature supporting benefits of VR. It has become clear that designers of interventions for VR are often citing benefits of using VR technology but are using these systems in ways that are perhaps contradictory and hindering their full potential

4.2. *VR system characteristics*

Just as there is no clear consensus on what defines VR, there is also no consensus of which system architectures can be used to deliver VR. Underlying system architectures range from desktop-based systems to fully immersive VR platforms that utilize HMDs. The most frequent system type is a desktop-based VR platform that presents a virtual environment onto a computer monitor that users can interact with through a variety of input device configurations such as a mouse and keyboard. In one case, Wade and colleagues (Wade et al., 2016, 2017; Zhang et al., 2017; Bian et al., 2019) utilized a USB G27 electronic steering wheel designed for racing video games to train individuals with ASD how to drive in an adaptive VR environment. This finding might be due to the fact that more immersive VR systems often require expensive hardware (Brooks, 1999) and can be difficult to design for. The issue is that these systems are referred to collectively as "VR." This is particularly problematic when considering those systems that appear to be similar to a video game, such as projection-based systems that utilized the Microsoft Kinect to project the movements of users onto a screen to complete game-like activities (Crowell et al., 2019; Cai et al., 2013; Lu et al., 2018). For example, in Pico's Adventure, participants interacted with the system by waving their arms which would direct lasers to shoot down alien spaceships with the goal of training joint attention skills (Crowell et al., 2019). While such systems have some commonalities with VR, they do not afford users the same level of interaction and immersion of a VR system. This raises the question of whether these are actually VR systems at all.

CAVE-based VR configurations exhibit similar issues. In these systems, virtual environments are projected onto walls or screens, but are done so in a more encompassing manner. Instead of being presented on just one screen, CAVE-based systems present the virtual environment on multiple screens to surround the user. The level of interaction provided by the system varies. In the Immersive VRET and Cognitive Behavioral Therapy System (Maskey et al., 2014; Maskey, McConachie, et al., 2019; Maskey, Rodgers, Grahame, et al.,

Table 5. *Design factors of VR projects/interventions for individuals with ASD as categorized using the elaborated model of learning in 3D virtual learning environments (*Dalgarno & Lee, 2010).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
VR Adaptive Driving System (Wade et al., 2016; Wade et al., 2017; Zhang et al., 2017; Bian et al., 2019)	The virtual platform supports driving tasks with variable complexity and difficulty. Drivers/learners can interact with traffic lights, pedestrians, and other drivers, all designed to behave naturalistically. A physics engine provides further realism. Virtual currency provides users with rewards for their performance.	Consistency of object behavior	A realistic physics engine that exerts force on in-world objects. Other in-world assets such as pedestrians, traffic lights, and other vehicles behavior in a way that mirrors the real world.
		Realistic display of environment	A realistic replication of Philadelphia was created that included a full model of its streets and buildings.
		Embodied actions	Users engage with the system through a variety of hardware that affords the embodiment of actions that emulate that from the real world. Examples include pressing down a brake and gas pedal to control the virtual vehicle.
iSocial (Wang et al., 2018; Schmidt, 2014; J. M. Laffey et al., 2014; J. Laffey et al., 2012; Stichter et al., 2014; Wang et al., 2016; Wang et al., 2017; M. Schmidt et al., 2014; Matthew Schmidt et al., 2012)	iSocial implements the 31-lesson social competence intervention (SCI-A) with high fidelity within a virtual environment that includes learning scaffolds and supports. Learners are represented as avatars. Communication is verbal and nonverbal. Users manipulate objects in the 3D space as they engage in goal-oriented curricular tasks.	User representation	In iSocial each user is represented by one's own avatar.
		Realistic display of environment	A variety of realistic environments were created where users could collaborate together in fantasy worlds including a boat, restaurant, castle, etc.
		Embodied actions	Users can control their avatar and manipulate and select objects within the virtual environment to complete curricular tasks.
		Embodied verbal and non-verbal communication	Users can communicate with other people within the environment through multiple modalities including verbal communication through a microphone and gestural through control of their avatar.
Gaze sensitive Adaptive Response Technology (Lahiri et al., 2015; Lahiri et al., 2011; Lahiri et al., 2011)	This virtual reality system was designed to administer and alter social interactions through the use of bi-directional conversation taking and feedback. The system measures physiological metrics of gaze to make predictions regarding engagement and adapts communication to the behavior of its users.	Consistency of object behavior	Virtual characters behave realistically.
		Realistic display of environment	Photorealistic backgrounds were used behind the virtual characters to provide naturalistic social contexts.
		Smooth display of view changes and object motion	Virtual scenes were designed to smoothly change to display new situations.
Immersive VRET and Cognitive Behavioral Therapy System (Maskey et al., 2014; Maskey, McConachie, et al., 2019; Maskey, Rodgers, Grahame, et al., 2019; Maskey, Rodgers, Ingham, et al., 2019)	This intervention was administered in a space called 'The Blue Room' where audio visual images were projected onto the walls and ceilings of a 360 degree seamless screened room. Participants could move around the space to freely interact with and navigate through the scenario. A therapist would control the scene being administered through an iPad. Participants would undergo several treatments that would evolve in exposure. Cognitive and behavioral techniques were used throughout.	Spatial audio	Visual and audio media are presented to users in an immersive CAVE environment.
		Realistic display of environment	Photorealistic environments are created that are often made from real-life social contexts of participants so they can be used to provide gradual exposure therapy to stimuli that invokes individual phobias.
Fire and tornado safety system (Self et al., 2007)	Virtual simulations were created that provided different levels of cueing including the sound of alarms going off, navigational wayfinding, redirected attention to relevant cues, and sensory cues of a fire including olfactory stimuli from ScentPalate®. Prompts and scaffolds were faded as participants went through the simulation repeatedly. By the end of the intervention participants had to assume control for most of the actions in the environment. The training simulation was based on buildings that participants were not familiar with.	Consistency of object behavior	Objects within the virtual environment maintain properties from the real world. For example, the fire object behaves realistically and sensory stimuli from this object is provided including olfactory stimuli .
		Realistic display of environment	A realistic building was created for users to navigate through as they practiced procedures like tornado and fire drills. Realistic visual cues and stimuli from the environment are included.
		Embodied Actions	Users are able to control a character through a virtual environment that evolves in complexities and gradually provides more control and embodiment to the user.

(*Continued*)

Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
AViSSS (Ehrlich & Miller, 2009)	AViSSS was designed to simulate everyday real-world contexts. Each environment has multiple scenarios where the user must solve a problem. Scenarios are designed around decision trees that encode social narratives. Participants interacted with the environment by clicking on responses that would appear at decision points. If an incorrect decision is made then the software would inform the participant about why that choice was poor. The last scene then replays so the user can make a better decision with the prior selection grayed out.	Realistic display of environment	Realistic social environments including hallways, restrooms, and cafeterias were created.
Bob's Fish Shop (Rosenfield et al., 2019)	This system was designed to allow users to successfully interact with the proprietor of a pet shop. Participants of the system used the Oculus Rift to navigate through the world as if they were actually inside the virtual environment. The script was designed in consultation with a BCBA to map out example conversations with variations. A professional voice actor was used to record the audio. In this environment, users begin in their home, go to a fish shop, examine the shelves, and then interact with the proprietor. The shop owner's mouth and body movements were animated to be naturalistic. The participant's verbal communications are processed and referenced to a response library to determine what actions should come next.	Embodied verbal and non-verbal communication	Users can communicate verbally through the use of a microphone. The system uses voice recognition to interpret what the user is saying and has an in-world character respond. The user is also able to communicate through the use of the Oculus Rift's wand controllers to gesture.
Virtual Joystick (Kim et al., 2015)	Virtual characters were created as a way of measuring how participants would use a joystick to position themselves closer or further from virtual avatars while attempting to identify six emotions expressed by the avatars, happiness, fear, anger, disgust, sadness, and surprise that were expressed at different levels of intensity.	Realistic display of environment	Users interact within a living room environment with virtual characters that present a range of realistic emotions and intensity.
		Embodied actions	Users are able to control an avatar with a joystick to position a character where they would in social scenarios based on the emotions that they perceive in virtual characters.
Rojo et al. CicerOn VR: Virtual Speech Coach (Rojo et al., 2019)	CicerOn is a serious game where participants can talk to different characters within virtual environments. It includes six levels that are gamified and based on Egyptian mythology. Users must solve riddles as they travel through different countries to find lost objects. After completing each level they must read aloud a final piece of text that is used to assess their speaking ability as well as advancing the narrative of the game. The different levels of the game provide users with gradual exposure to the fear of public speaking. A speech recognition system is used to evaluate the responses of users which allows for formative assessment and improvement on their abilities. A HMD is implemented with the goal of helping users transfer what they learn.	Embodied verbal and non-verbal communication	Users are able to read a series of artifacts out loud that the system interprets and provides feedback to.
		Embodied actions	Users can control their viewport and interact within the environments to find clues and progress through the game.
		Realistic display of environment	Environments were created based off of real-world locations.
Eye gaze VR (Grynszpan et al., 2019)	This system utilized an eye-tracker device that was capable of monitoring the gaze of participants. A bust of a male avatar was created and programmed to follow the gaze of the participant. In this system some of the virtual characters would follow the gaze of participants and others would not.	Embodied actions	Eye gaze of interactions within the system are controlled by the user which directs the attention of virtual characters.

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Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
IVR (Herrero & Lorenzo, 2020)	This system was designed to provide users with a familiar environment. A generic garden and school context were created to facilitate participants' adaptation of social and emotional skills as these settings are familiar to participants and are filled with social interactions. Avatars were created with different personalities and appearances to provide realistic social spaces for practice. Avatar behaviors were animated to be realistic. Avatar responses and behaviors were controlled by the researcher.	Realistic display of environment	Realistic environments of a garden and school were created to provide a training context familiar to the participants. Spatial environment was designed to be realistic.
		Embodied verbal and non-verbal communication	Users are able to engage and communicate through voice and gestures with in-world avatars. Those interactions and responses are triggered by predefined options that include realistic gestures, facial expression, and lip synchronization with the corresponding audio, recorded by a real human being.
		Embodied Actions	Through the Oculus Rift and its wand controllers users take on an avatar that is used to manipulate and interact with assets within the virtual world.
CRETA (Zhang et al., 2020)	CRETA is a virtual environment where two users play games either with each other or with the system's intelligent agent. These games were designed to withhold information or require simultaneous movement in order to promote collaboration and communication between players.	Embodied verbal and non-verbal communication	Users can verbally communicate through a microphone. If they are playing with an agent-avatar then the system uses voice recognition to interpret the speech and respond accordingly. Users are able to communicate and collaborate through consistent, controlled, and replicable interactions.
		Embodied Action	Users are able to manipulate objects within the environment in collaboration with others or a virtual agent to solve problems.
Facial Recognition VR (Bekele et al., 2014) (Bekele et al., 2012) (Bekele et al., 2013)	Virtual characters were created to present 28 trials of 7 emotional expressions at four levels of intensity. After realistic facial expression animations were presented a menu appeared where participants were given choices and asked to identify the emotion.	Consistency of object behavior	Virtual characters react and behave in a realistic manner.
		Realistic display of environment	Each avatar was rigged with a skeletal structure consisting of 94 bones. Twenty of these bones were involved with the face structure that was used for facial emotional expressions. Since the main focus of this project was displaying facial emotional expressions, greater emphasis was given to the face structure.
VR-JIT (Smith et al., 2015; Smith et al., 2014; Smith et al., 2020)	Virtual characters were created to present 28 trials of 7 emotional expressions at four levels of intensity. After realistic facial expression animations were presented a menu appeared where participants were given choices and asked to identify the emotion.	Embodied verbal and non-verbal communication	Users are able to respond to a virtual character that is conducting a simulated job interview. Individuals are provided with multiple methods of responding including speech which is parsed through voice recognition software.
IVRT research (Lorenzo et al., 2016)	This immersive virtual reality platform allows users of the system to improve and train on emotional skills by interacting with different in-world avatars and to perform emotional recognition tasks while engaging in social contexts such as a party and a classroom The CAVE platform presents a frontal view of the environment and the other is placed on a platform which allows it to project from below. The assets and avatars of the represented scenes adapt to the behavior of users of the system. A camera tracks where users are in the environment and adapts to their behavior	Realistic display of environment	A classroom and party scene were created that included realistic avatars and emotional expressions.
		Embodied actions	A camera system on a robotic arm tracks the user's facial expressions to detect their mood and update the system accordingly. The camera also determines the pose of the users and allows them to interact with the environment.
Virtual Dolphinarium (Cai et al., 2013) (Lu et al., 2018)	This system is a virtual dolphin interaction program that allow children with autism to act as dolphin trainers. The goal of the program is to allow users to interact at a realistic poolside and to learn (nonverbal) communication through gesturing and commands with the virtual dolphins. Immersive visualization and gesture-based interactions are implemented through a curved screen spanning 320 degrees, a projection system, and a Microsoft Kinect.	Realistic display of environment	A virtual pool was created and based off of a pink dolphin lagoon experience for individuals with autism. The virtual pool includes levels of realism such as high fidelity water ripples, animated dolphins that have real-time collision avoidance and collision detection algorithms.
		Embodied verbal and non-verbal communication	Gesture-based non-verbal communication is used as a way for the participant to communicate with dolphins in the virtual environment.
		Embodied actions	A Microsoft Kinect is calibrated to the movement of a user's actions so that their gestures and actions are able to interact with objects within the virtual world.

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Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
Haptic-Gripper Virtual Reality System (Zhao et al., 2018)	The Haptic-Gripper Virtual Reality System was designed to provide analysis and opportunities for practice of fine motor skills in an adaptive system with immediate auditory, haptic, and visual feedback. It is capable of detecting the grip and hand location of users so that it can provide feedback and guide them through completing several engaging virtual fine motor tasks. System was made in Unity.	Kinesthetic and tactile force feedback	Use of a haptic system that is able to measure the user's tactile and force feedback so they correspond to the virtual activities. Includes haptic feedback such as friction and spring force.
		Embodied actions	The actions of the user's fine motor hand skills are translated to the virtual system through the use of a haptic device.
AS System (Kuriakose & Lahiri, 2017) (Kuriakose & Lahiri, 2015)	The anxiety system (AS) was designed to allow real-time measurement of performance and associated physiological indexes that can be mapped to one's anxiety while interacting within social tasks in a virtual environment. Within this desktop-based platform, 24 different social stores are presented to users to expose them to social contexts.	Consistency of object behavior	Realistic non-playable characters are presented in the virtual environment that are able to behave with consistency of their real-world counterparts including expressions and mannerisms.
E-VISP (Babu et al., 2018)	This social communication system system is composed of 3D environments that emulate real-life social contexts. The system is designed to present an interactive task environment that begins with a social narrative and then moves to a questionnaire phase. Nine social stories were created and modeled to include behaviors that would attempt to direct the gaze pattern of participants.	Consistency of object behavior	Realistic non-playable characters are presented in the virtual environment that are able to behave with consistency of their real-world counterparts including expressions and mannerisms. The avatars were programmed to demonstrate a mixture of gaze patterns.
		Realistic display of environment	Social contexts were made in Google Sketchup to emulate the real world
Immersive VR System (Halabi et al., 2017; Halabi et al., 2017)	This VR system consisted of an interactive scenario-based task that utilized speech recognition and turn-taking role play to improve communications skills of autistic children. In this system, the subject is automatically navigated through the virtual environment. After arriving inside of the virtual classroom a virtual teacher introduces themselves and goes through a series of tasks. Voice and action monitoring is tracked to record a response.	Realistic display of environment	A realistic classroom and school setting were created because it is seen as a social space where individuals with autism have many interactions
		Consistency of object behavior	Realistic non-playable characters are presented in the virtual environment that are able to behave with consistency of their real-world counterparts including expressions and mannerisms. The virtual teacher and other students interacted through realistic gestures.
		Embodied verbal and non-verbal communication	A voice recognition system was implemented. It would react when a participant began talking so measure their social-communicative response times. Gestural movements were also tracked as a way of giving users opportunities to use non-verbal communicative skills.
		Embodied actions	A LEAP Motion device was used to map the user's actions into the virtual system
Pronunciation VR platform (Chen et al., 2019)	This 3D virtual tutor was designed to act as a multimodal and real-data-driven speech production tutor to provide internal and external models of realistic pronunciation.	Consistency of object behavior	The 3D model of the character's body would animate and change in order to generate realistic pronunciation models for users of the system to observe. Animations and behaviors were modeled off of real-world people to provide object behavior fidelity.
AS Interactive (Parsons et al., 2005) (Parsons et al., 2000) (Rutten et al., 2003) (Mitchell et al., 2007) (Parsons et al., 20042004) (Parsons, 2005)	Two social contexts were created with the main task of navigating social spaces and trying to find a place to sit down. Different versions of each environment were created that evolved in complexities and forced users to ask questions and to reflect upon why they could not sit down with people they did not know.	Realistic display of environment	The virtual scenes were designed to provide a realistic display of the physical aspects of the café and bus environments.
		Embodied actions	Participants used a joystick to navigate and a mouse to activate objects (e.g. sitting down by clicking on the chair) or perform interactive tasks in the environment.

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Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
VR4VR (Bozgeyikli et al., 2017)	The VR4VR system was designed to provide vocational training opportunities around transferable skills of cleaning, loading the back of a truck, money management, shelving, environmental awareness, and social skills. Each skill task is structured across three sessions that evolve in fidelity and complexities.	Realistic display of environment Consistency of object behavior Embodied action	Physically realistic representations of the training environments were created Real world complexities and distractors are added into the system that behave in a consistent manner. Users emulate the real motor functions needed to learn the vocational tasks being trained on in the system. Real-life items are scanned into the system and act as mediators between the virtual and real world. For example, users hold a pipe in the cart scenario to give them a physical connection to the action they are embodying.
Street-crossing environment (Josman et al., 2008)	In this system, a user is represented with an avatar which is faced toward a zebra crossing at the start of each of the nine levels. The difference in each level is the number of cars, the traffic patterns, and their speed. Users who successfully cross the street automatically advance to the next level. If a user is hit by a car then a crashing animation is played and they replay the level until completion.	Realistic display of environment Consistency of object behavior Embodied actions	A realistic four-lane street was created for users to practice street crossing skills in. Traffic lights, patterns, and vehicles behaved in a consistent and realistic manner. Users control an avatar as they look out for traffic patterns and cross the street. They can change which way they are looking and can control the avatar as they cross the street.
VR-Tangible Interaction System (Jung et al., 2006) (Jung et al., 2006)	This system has three components that are designed to combine coordination and motor ability, social skill training, and sensory integration. User's complete a variety of game-like activities to provide baseline measurements of their abilities. Actions of users are projected onto a screen-based system.	Embodied actions	Participants' actions on physical in-world devices are reflected on the screen as they perform tasks.
Emotional and social adaptationVR Intervention (Ip et al., 2018) (Yuan & Ip, 2018)	This VR system provides users with content in the form of learning scenarios to practice emotional and social adaptation skills facilitated by a trainer. Scenes are projected in a CAVE environment and user actions are mapped into the environment through motion tracking.	Realistic display of environment Embodied actions	Realistic training contexts are presented across a variety of social spheres including classrooms, in a bus, at home, and more. User actions are tracked and projected into the social scenes in the CAVE environment.
Block Challenge (Parsons, 2015)	Block Challenge is a two player collaborative game where users engage with each other to collaborate and solve challenges around manipulating blocks. The goal of the system is to support communicative perspective taking skills.	Embodied verbal and non-verbal communication Embodied actions	Users communicate with each other to complete puzzles that are solved with blocks. They can communicate through a microphone or through their non-verbal actions. Users are able to manipulate and control blocks within the environment to solve challenges.
Virtuoso-SVVR (Schmidt et al., 2019)	Virtuoso-SVVR is part of an instructional strategy to deliver training on catching public transportation in a university setting for members of an adult day program. In this platform the skills of catching a shuttle bus are modeled to users as they watch 360 degree scenarios.	Embodied actions Realistic display of environment	Users are able to control their viewpoint as their perspective is automatically guided through the virtual 360 degree campus. 360 degree footage of the training context was shot with high definition cameras to provide a realistic display of the exact environment the skills are being trained for.
Street Crossing Platform (Dixon et al., 2019)	The VR environment was made up of 360 degree videos of real streets from the participants' community. Users watched the videos and responded to questions from a facilitator	Embodied actions Realistic display of environment	Participants could control their view of view by turning their head within the HMD. 360 degree videos were captured by a high definition Samsung Gear camera to provide a realistic training environment from the community that participants were familiar with.
Modified Virtual Errands Task (Rajendran et al., 2011)	In this platform, users are placed in a virtual school and put into the role of a pupil where they complete errands that their teacher sends them on. The tasks are designed to be ones that might be plausible in a real school setting such as checking a bulletin to see when an exam is taking place. Users navigated through the building through the use of a mouse.	Embodied actions Realistic display of environment	Users are able to control their character to navigate through a school building to complete tasks. The school model is based off of a real university building.

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Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
Virtual Mall (Trepagnier et al., 2005)	The Virtual Mall is a joystick-navigable, first-person mall that is presented to users on a monitor. The goal of the platform is for users to navigate through the mall that is filled with social obstacles.	Realistic display of environment Consistency of object behavior	A mall environment was made to provide a social context that is familiar to participants. Non-playable characters fill the virtual space to create situations that are identical in terms of spatial properties and similar to that of social implications. These characters take on consistent object behavior similar to the real world.
		Embodied actions	Participants use a joystick to control a character through a virtual mall while judging socially appropriate responses to objects and other people around them. Placement and orientation of the virtual humans creates situations that are identical in terms of spatial properties (e.g. space between humans and walls, or between obstacles and walls) but differ importantly in social implications (e.g., passing between a person and a store window to which her back is turned, versus passing between two characters facing each other at a conversational distance vs. passing between two advertising signs)
Virtual Conversation Partner (Trepagnier et al., 2005) (Trepagnier et al., 2011)	This virtual environment is a simulated conversation platform for teaching occupationally important social communication skills such as interviewing techniques. A real-life actor was used to record and provide scripted responses to actions that the user can input through a dialog system.	Consistency of object behavior	Virtual characters react to responses by users with realistic mannerisms and expressions. If things go too poorly they will get up and leave the room and end the session.
Virtual Travel Training (Simões et al., 2018)	This serious game places users into a 3D city and provides them with a series of tasks that involve taking buses to reach specific destinations. Busses in this environment follow in 4 predefined routes within the city. The player can enter any of the buses, must validate their ticket, pick a seat, and then request a stop when they have reached their destination. Players can choose between 7 tasks of varying difficulty and complexities.	Realistic display of environment Consistency of object behavior Embodied actions	A realistic replication of a city and bus were created to provide different levels of training. Objects within the environment behave like those from the real world including objects/elements, such as people, traffic, and dogs. Users are able to control their view by turning their head in the Oculus Rift HMD. A USB game controller was used to navigate their character through the environment.
JobTIPS (Strickland et al., 2013)	In the virtual world training platform users connect to a digital interview location where simulations are remotely led by a clinician at a different physical location. The clinician assumed the role of an interviewee and the participant took on the role of the individual being interviewed. Users sat across from one another in a virtual office space to practice job interviewing skills.	Embodied verbal and non-verbal communication	Users are able to practice job interview skills through the use of both verbal and non-verbal communication supported by a microphone and through avatar gestures.
Crossing the Street (Strickland, 1997)	This virtual street crossing environment provided users with a simplified, safe, and controlled context to practice pedestrian skills.	Realistic display of environment Embodied actions	Textured buildings and streets were created. Environments were simplified with many details left out to reduce distractions. Users are able to have their actions embodied through the use of a HMD and motion tracking controllers.
Floreo PSM (Parish-Morris et al., 2018)	The PSM includes multiple scenarios, including an officer walking by without direct interaction, officers approaching participants to ask questions, being asked to provide identifying information, and more. Scenes are varied to take place during both the daytime and nighttime. Scripts from the cops are prerecorded but can be controlled by the administering therapist.	Realistic display of environment Embodied actions	Realistic community settings were provided that users can interact within Users can change their viewport through the use of the light weight mobile HMD

(*Continued*)

Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
Blood drawn exposure therapy (Meindl et al., 2019)	In this 360 degree video environment users watch a video of blood being drawn to help them gradually become used to the procedure through exposure therapy. A video is presented in a HMD of blood being drawn with an Apple Pencil being used to simulate the needle prick. Exposure is presented in comfortable and safe settings at home and then in the doctor's office.	Realistic display of environment	A 360-degree video of a blood draw was developed using the Insta360 One VR camera to provide a high fidelity environment
		Kinesthetic and tactile force feedback	Apple Pencil stylus used to simulate the needle insertion.
		Embodied actions	Users are able to turn their head to look around the 360 degree video environment.
3D Empathy System (Cheng et al., 2010)	This system was designed to provide learners with social events where empathetic contexts can be emphasized. It allows users to select expressive avatars to represent themselves, express their emotions to others, and to use and improve empathy via interaction with others. Scripted questions are designed to elicit questions of empathy from participants. Training takes place in a virtual restaurant as restaurants are public places in which people are in contact with others.	Realistic display of environment	Simulated the real-world through 3D animation and virtual scenes.
		User representation	Users can select expressive avatars to represent themselves.
		Embodied verbal and non-verbal communication	Users are able to communicate via text or speaking. Users can control their avatar's facial expressions
3D-SU system (Cheng et al., 2015)	This system provides users with simulated environments that they can be immersed within to promote social understanding skills. Users are able to interact with objects in the environment and are immersed with a HMD. Social events are presented to users that take place within a 3D virtual bus stop and classroom environments which were selected because subjects frequently encounter these social settings.	Realistic display of environment	Simulated social spaces were created to provide relevant places for the practicing of skills.
		Embodied action	Users can interact with objects in the environment through mouse and keyboard clicks and can control their view with the HMD.
Public Speaking Intervention (Jarrold et al., 2013)	The virtual social attention, public speaking task was delivered via a HMD that tracked the movement of users. Participants practiced public speaking skills in an environment that provided a virtual audience of peers. Cues were included as a way of prompting fixation on objects and analyzing task difficulty.	Realistic display of environment	A realistic 360-degree virtual classroom was rendered.
		Consistency of object behavior	Virtual student avatars were programmed to exhibit subtle eyeblink and head motions typical of an audience of peers.
		Embodied action	Head orientation and rotational motion along three rotational axes were dynamically tracked and embodied in the environment.
Virtual Reality Social Cognition Training (Kandalaft et al., 2013; Didehbani et al., 2016)	The VR-SCT provided realistic opportunities to engage in, practice, and to attain feedback on activities within social spaces. After logging into the multi-user environment, an online guide directed users to social situations taking place at one of the virtual locations. Scenarios were devised to emphasize learning objectives around various social skills such as resolving conflict, meeting new people, and interviewing for a job.	Realistic display of environment	A variety of realistic settings were created to provide dynamic opportunities for social training.
		User representation	Avatars representing the user in the virtual world were modeled to resemble each participant
		Embodied verbal and non-verbal communication	Users could communicate through a microphone and through arm and body gestures of their avatar.
		Embodied actions	Users could interact with the environment through their avatars that were driven by a standard QWERTY keyboard and mouse.
Interaction Training (Ke & Im, 2013; Ke et al., 2015)	The system was composed of three social interaction tasks including one concerning the recognition of gestures and expressions, responding to and maintaining an interaction, and initiating and maintaining an interaction. During each session an adult facilitator logged in and actively interacted with other users in the environment. They provided support and guidance.	Realistic display of environment	A variety of realistic settings were created to provide dynamic opportunities for social training.
		Embodied actions	Users controlled their avatar as they manipulated the environment, moved throughout, and maintained social interactions.
		Embodied verbal and non-verbal communication	Users could interact via a microphone or a gestural system
Hand-in-Hand (Zhao et al., 2018)	This system supports naturalistic social interactions, promotes communication within game play, and gathers user performance and communication in real time. The goal of Hand-in-Hand is to collaborate with another user to solve a puzzle game.	Embodied verbal and non-verbal communication	Supports gaze, gestural, and voice communication.
		Embodied actions	The Leap Motion device recognizes the players' hand locations and gestures as the control signals to manipulate virtual objects.

(*Continued*)

Table 5. (Continued).

Project and References	System Description	Identified Design Factors (Dalgarno & Lee, 2010)	Description of Design Factors
Eye-gaze system (Grynszpan et al., 2012)	In this system, participants would look at the face of a virtual character while addressing them. The virtual character would then describe a situation and in the process would say a sentence that could be interpreted in two distinct ways according to the context. That context was provided by the facial expressions of the avatar and left up to the user to recognize and determine. Five basic emotions (disgust, joy, fear, anger and sadness) were utilized in the system.	Consistency of object behavior	Virtual characters made realistic facial expressions and mannerisms.
Pico's Adventure (Crowell et al., 2019)	Pico's Adventure was a full-body interaction collaborative system developed to help children with ASD learn and practice social abilities needed in collaboration such as reciprocity, imitation, joint-attention, and cooperation. Children played games together that required cooperation such as having to employ joint attention to direct a laser to free their parents from spaceships.	Embodied verbal and non-verbal communication Embodied actions	Users can communicate through the built-in microphone in the Kinect or through their gestures that are displayed on screen through the Kinect. Microsoft Kinect reflects the behavior of users into the system
Decoding Social Interactions (Jacques et al., 2018)	In this system users were coached through 5 social scenarios by a virtual coach that helped them decode social interactions and their contexts including emotions, possible actions, and behaviors that could be applied and practiced. These activities took place within Psyche, a fully immersive stereoscopic and wireless 6-wall CAVE-Like system where participants can move freely with a wand tracker.	Embodied actions Realistic display of environment	Participant actions were recorded with a wand tracker as they moved freely throughout the CAVE Social scenarios that represent common places of gatherings were presented to users so they could practice decoding and responding to interactions.
VR-CR (Wang & Reid, 2013)	In this VR platform the user has to make a similarity judgment between a movable target object and a multi object context that is displayed on the screen. They are able to manipulate and drag virtual objects to different locations in the environment.	Embodied actions	Motion-capture technology was incorporated using a tracking webcam which projected their movements into the virtual environment.
VLSS (Volioti et al., 2016)	Social stories are presented to students within a virtual environment. These include contexts that involve solving problems at home, handling dilemas, and how to handle a situation where they feel anger from their classmates. Users are presented with text and images on an interactive whiteboard to explain these social stories and are then given multiple choice options on how they should respond.	Embodied actions Realistic display of environment	Students control an avatar as they navigate through the environment. They use a keyboard and follow paths through the environment to complete the intervention. The user is able to choose to interact with objects such as sitting at a desk. Authors describe the system design as being the best possible realistic representation of school premises
VESIP (Russo-Ponsaran et al., 2018)	VESIP is an automated, interactive, computer-delivered assessment that uses 3D game technology in which respondents play the role of a customized avatar and engage in social situations. In each scenario, the respondent's avatar engages in a challenging social situation, and a friendly helper character. Questions are posed to the user which can be responded to through multiple-choice or slide-based systems.	User representation	Users are able to design their own character which then becomes part of the social scenes.

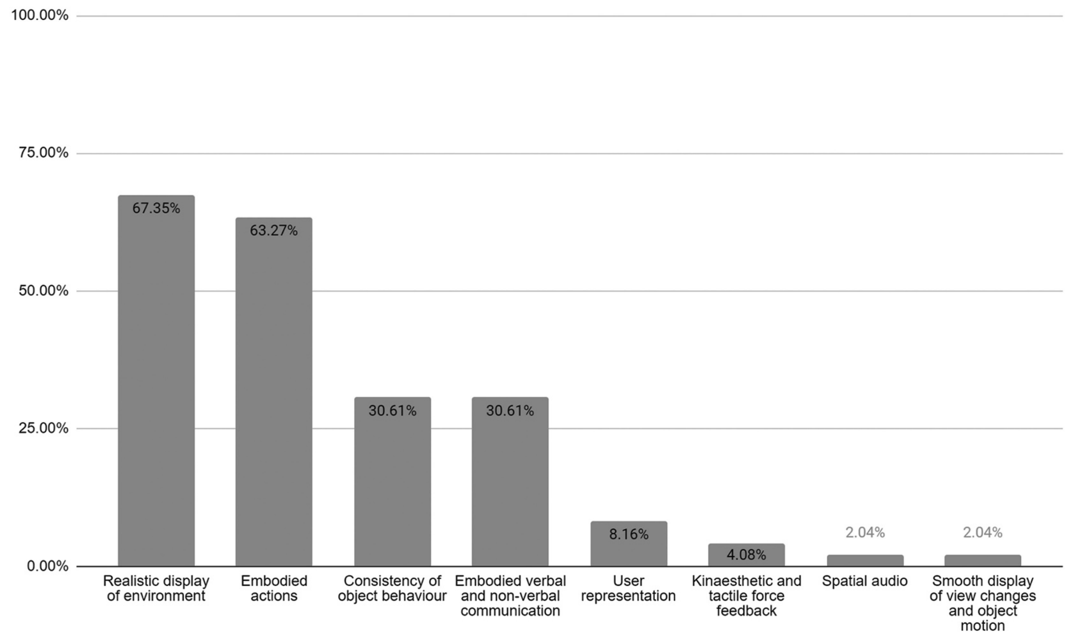

Figure 6. Design factors instantiated across VR projects/interventions by percent.

2019; Maskey, Rodgers, Ingham, et al., 2019), users are placed within a 360-degree CAVE where scenes are controlled by an administering therapist. Users are passive observers to scenarios that evolve in complexities to help treat phobias. In another example, the Decoding Social Interactions (Jacques et al., 2018) system allows users to interact within a L-shaped CAVE and have their motions tracked through a wand controller. This device allows for greater embodiment of user actions and enables participants to take a more active role in the training of social skills. Both systems are characterized as being VR platforms but clearly offer users vastly different experiences.

In a similar vein, mobile-based VR systems are emerging, in which users are often placed within a light-weight HMD and engage within a spherical video-based virtual reality (SVVR) training context (Meindl et al., 2019; Schmidt et al., 2019). In these systems, users are presented 360-degree videos as they wear a headset. Users typically have limited control and are passive observers to video-based multimedia or scripted events. These findings highlight the variability of VR systems that are being used to provide interventions for individuals with ASD, and they also align with the conclusions of other work in the field that note that few fully immersive HMD-based VR systems have been used (Bozgeyikli et al., 2018; Newbutt et al., 2016). However, the lack of any standard, agreed-upon characterization or definition in this field of what constitutes VR in general, and what constitutes different VR architectures specifically (including whether some architectures should be considered VR at all) raises concerns about efficacy claims of VR for individuals with ASD. In the future, researchers will need to confront this issue. Until then, researchers are urged to provide precise descriptions of how VR is operationalized in their particular contexts.

4.3. Distinguishing characteristics of VR in systems designed for individuals with ASD

Results from our third research aim indicates that the most commonly designed characteristic of a virtual learning environment that's been proposed as having potential learning benefits (Dalgarno & Lee, 2010) is that of creating a realistic display of the environment. This finding confirms empirically what others have suggested (e.g., Parsons, 2016), that researchers tend to design their VR environments "towards a closer fit with the real world" (p. 154). The second most frequent design factor was that of embodied action within the virtual environment. Dalgarno and Lee (2010) highlight the centrality of embodied action toward identity construction. This consideration of embodiment brings up an important issue concerning the design of VR systems and their underlying hardware and modalities for interaction. That is, that the interactions between the learner and the system are often being considered, but it is unclear if these interactions are being intentionally designed in a way that can fully exploit the purported benefits of the technology. The findings presented in Table 5, highlights this issue as it shows the many ways that this design challenge of embodiment is being considered and how it can be achieved through a variety of configurations.

For example, designing to allow for the embodiment of a user's actions can be achieved in many ways. In the Immersive VR System (Halabi et al., 2017; Halabi et al., 2017) a LEAP Motion device is used to capture and translate a user's movement into the virtual environment. In the Virtual Dolphinarium (Cai et al., 2013; Lu et al., 2018) a Microsoft Kinect picks up simple movements such as arm and hand gestures that can be projected into a game-like system. In the Virtual Joystick (Kim et al., 2015), users are able to control an avatar with a joystick to position their character within social scenarios. In the VR Adaptive Driving System (Wade et al., 2016, 2017; Zhang et al., 2017; Bian et al., 2019), users interact with a system made up of realistic vehicular input devices to control a virtual car that can drive around a full-scale city. In the Public Speaking Intervention (Jarrold et al., 2013), a user's head orientation and rotational movement along three axes were dynamically tracked and embodied in the environment. All of these examples convey a possibility for learner interactions that can promote the embodiment of a users' actions within a virtual environment. However, it is unclear if these interactions afford its users the possibility to engage in a meaningful way that can promote learning outcomes. As seen in Figure 6, many of these VR systems were designed to promote the development of social skills which is an innately complex interaction composed of a multitude of verbal, non-verbal, and emotional sub-skills. Yet the vast majority of VR systems are desktop-based interfaces where users interact with, gesture, and have their actions embodied into the system through rigid motions that are mediated through unnaturalistic peripherals and interfaces (e.g. clicking a button on their keyboard or mouse to move their arm). This finding presents what seems to be a disconnect between intended learning outcomes and how VR systems tend to be designed for this population. Also of concern is that because of the disparate state of VR systems and their varied configurations, characteristics, and design instantiations, researchers will have difficulties in systematically unpacking how VR systems can be developed to promote generalization.

What has become clear is that design factors have been instantiated across the literature in a wide number of considerations (see Table 5), and the way that the VR intervention is designed, beginning with the VR architecture and system type, greatly impacts the affordances and possibilities for interaction with the system. Given the rapid pace of adoption of VR by the public (Bagheri, 2016), and the emergence of commercially affordable HMD (Newbutt et al., 2016), interest in using this technology for individuals with ASD continues to grow (Parsons, 2016). However, difficulties with designing to promote generalization remain. The field is laden with researchers who are trying to develop VR solutions that vary in their target audience and target outcomes. If VR systems are to be designed in a way that can meaningfully promote targeted outcomes and potentially generalization, then VR developers need to take a more systematic approach to defining the technology, using a model like Dalgarno and Lee (2010), and begin to consider how the interactions between the learner and the system can facilitate the learning process.

4.4. Implications for practice

As emphasized in this review of the literature, designing VR interventions for autistic populations constitutes a wicked problem that is steeped in complexity. Although it is generally accepted that developing VR interventions in the field of autism research is fraught with challenges, little has been written to chronicle how practitioners can address these constraints (Glaser et al., 2021). Compounding this problem is that there are multiple gaps in the literature such as a paucity of design precedent and an unfortunate failure to include participants in the design of interventions (Parsons et al., 2020). Given the heterogeneous nature of autism, practitioners will likely find that there is no VR system, technology, or affordance that independently influences intervention efficacy. Importantly, the benefits and affordances of VR for individuals with ASD are often alluded to in the literature; however, we have been unable to locate any research that explicitly considers how benefits and affordances are explicitly considered in system designs to advance intended outcomes. Rather, design considerations are not often reported, and those that are tend to derive from small case observations and not from strong evidence or comparative studies (Bozgeyikli et al., 2018). Practitioners should consider this gap with a careful reflection on prioritizing principles of respect and dignity for autistic participants and should engage in research with this population. We therefore suggest that practitioners should adopt practices that include and involve participants and that are sensitive to the vulnerabilities of the target population.

4.5. Limitations

Findings and implications of this systematic review should be considered in light of the following limitations. Procedures used in this manuscript deviate somewhat from suggested guidelines for conducting systematic literature reviews (Davis et al., 2014; Kitchenham, 2004; Moher et al., 2009) including: (1) data was extracted by a single researcher, (2) multiple publications were included from the same dataset or research projects, and (3) some projects did not name their interventions which led to difficulties determining if a VR platform was unique.

The first point means that some of the data extracted may be erroneous. This limitation is in line with other research in the field that suggests the difficulties in conducting large scale qualitative reviews of the literature (Belur et al., 2018; Campbell et al., 2013). Other research has shown that difficulties arise with validating data when a large number of studies are provided or when the data is complex (Belur et al., 2018; Kitchenham et al., 2009), even if data definitions and extraction guidelines are provided in a protocol (Brereton et al., 2007).

The second point refers to guidelines proposed in by Kitchenham (2004) that stresses the importance of excluding multiple publications that use the same data set as doing so can impact the bias of results, and suggests that the most recent report should be the one included. With respect to this guideline, we included all studies from a dataset because of the nature of our research questions. We were not looking at reporting study outcomes but were rather interested in the qualitative described conditions of VR systems and designs. Therefore, it was important to include all manuscripts from the same dataset as reports often did not include all of the relevant data that we were trying to extract or the information was ambiguous and required triangulation across multiple manuscripts to confirm the data.

Lastly, we found that many designers of VR interventions did not give their system a name that would help identify the project. There were cases where multiple manuscripts presented on data that appeared to be related but did not explicitly provide those connections. In some cases, we were able to determine if a manuscript was part of an existing project because they shared common assets across manuscripts. For example, one project used the same screenshot of the system in multiple papers so we were able to group them together. Due to this limitation, it is possible that there are errors in the organization.

4.6. Conclusion

In conclusion, the findings from this systematic literature review suggest that VR interventions for individuals with ASD vary in conceptualizations of the term which has implications on how the platform itself is designed. While researchers tend to cite purported benefits of VR technologies and virtual worlds, the designs of the systems greatly impact the possibilities for learner interactions and how these learning benefits can be realized. Most research in the field has been conducted on desktop-based VR systems that use a variety of input devices and configurations. This finding suggests that designers of VR systems may be creating solutions that are not taking full advantage of the purported benefits to virtual environments such as increased immersion, fidelity, and active learning participation (Dalgarno & Lee, 2010).

Creating VR spaces is fraught with challenges and it is unclear how the nature of learner interactions within a virtual context can impact learning outcomes for individuals with ASD. That is, there is still great uncertainty that exists concerning how the ideal properties of VR can be brought together to promote the development of different skills. A review of the literature indicates that researchers are exploring a range of VR technologies, to promote a range of skills and treatments, for a wide range of audiences, and with an even greater range of design implementations. This finding makes it hard for future researchers to make their own design decisions, as there is not much that exists concerning how to intentionally design for generalization of specific skills within VR spaces. Echoing the conclusions from another manuscript in the field, perhaps it is time for researchers to stop asking questions about if VR, or other technologies, work for individuals, and should instead focus on understanding which technologies work for whom, in which contexts, with what kinds of support, and for what kinds of tasks or objectives (Parsons, 2016).

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About the Author

Noah Glaser, is an Assistant Professor of Instructional Design & Technology at Old Dominion University. Noah is a developer of educational interventions that utilize emerging learning technologies such as virtual reality, video games, and mobile devices. His work tends to focus on providing technological solutions to promote inclusion, access, and equity.

Matthew Schmidt, is an Associate Professor of Educational Technology at the University of Florida, faculty in the Institute for Advanced Learning Technologies, and director of the Advanced Learning Technologies Studio. His work includes design and development of educational courseware with a focus on individuals with disabilities and their families/caregivers.

Appendix A

Database	Search Query
PubMed	((((((((((((((((((((((“virtual reality”[MeSH Terms] OR (“virtual”[All Fields] AND “reality”[All Fields]) OR “virtual reality”[All Fields]) OR (virtual realities[All Fields] OR virtual reality[All Fields] OR virtual reality,[All Fields])) OR (virtual[All Fields] AND (“learning”[MeSH Terms] OR “learning”[All Fields]) AND (“environment”[MeSH Terms] OR “environment”[All Fields]))) OR (virtual learning environment[All Fields] OR virtual learning environments[All Fields])) OR (“virtual reality”[MeSH Terms] OR (“virtual”[All Fields] AND “reality”[All Fields]) OR “virtual reality”[All Fields])) OR (virtual realities[All Fields] OR virtual reality[All Fields] OR virtual reality,[All Fields])) OR (“Proc IEEE Virtual Real Conf”[Journal] OR “vr”[All Fields])) OR (virtual[All Fields] AND (“environment”[MeSH Terms] OR “environment”[All Fields]))) OR (virtual environment[All Fields] OR virtual environments[All Fields])) OR (virtual[All Fields] AND (“WORLD”[Journal] OR “world”[All Fields]))) OR (virtual world[All Fields] OR virtual worlds[All Fields])) OR virtual-world[All Fields]) OR (virtual world[All Fields] OR virtual worlds[All Fields])) OR (collaborative[All Fields] AND (virtual learning environment[All Fields] OR virtual learning environments[All Fields]))) OR (3D[All Fields] AND (virtual learning environment[All Fields] OR virtual learning environments[All Fields]))) OR (three-dimensional[All Fields] AND (virtual learning environment[All Fields] OR virtual learning environments[All Fields]))) OR ((three[All Fields] AND dimensional[All Fields]) AND (virtual learning environment[All Fields] OR virtual learning environments[All Fields]))) OR (3d[All Fields] AND virtual[All Fields] AND worlds[All Fields])) OR (3d virtual world[All Fields] OR 3d virtual worlds[All Fields])) OR MUVE[All Fields]) OR (“caves”[MeSH Terms] OR “caves”[All Fields] OR “cave”[All Fields])) OR (“smart glasses”[MeSH Terms] OR (“smart”[All Fields] AND “glasses”[All Fields]) OR “smart glasses”[All Fields] OR (“head”[All Fields] AND “mounted”[All Fields] AND “display”[All Fields]) OR “head mounted display”[All Fields])) AND (“1995/01/01”[PDAT]: “2020/12/31”[PDAT]) AND “humans”[MeSH Terms] AND English[lang]) AND (((((((((((((“autistic disorder”[MeSH Terms] OR (“autistic”[All Fields] AND “disorder”[All Fields]) OR “autistic disorder”[All Fields] OR “autism”[All Fields]) OR (autism[All Fields] OR autism’[All Fields] OR autism’s[All Fields] OR autism1[All Fields] OR autism360[All Fields] OR autismaid1[All Fields] OR autismand[All Fields] OR autismate[All Fields] OR autismcare[All Fields] OR autismcenter[All Fields] OR autismcrc[All Fields] OR autismdata[All Fields] OR autisme[All Fields] OR autisme’[All Fields] OR autismeexpertise[All Fields] OR autismeforeningen[All Fields] OR autismen[All Fields] OR autismes[All Fields] OR autismespectrum[All Fields] OR autismespectrumstoornis[All Fields] OR autismespectrumstoornissen[All Fields] OR autismespekterforstyrrelser[All Fields] OR 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autismusbehandlung[All Fields] OR autismusforschung[All Fields] OR autismusspektrumstorungen[All Fields] OR autismussyndrom[All Fields] OR autismustherapiezentrum[All Fields] OR autismuszentrum[All Fields])) OR (“autistic disorder”[MeSH Terms] OR (“autistic”[All Fields] AND “disorder”[All Fields]) OR “autistic disorder”[All Fields] OR “autistic”[All Fields])) OR (autis[All Fields] OR autischen[All Fields] OR autischer[All Fields] OR autisense[All Fields] OR autisic[All Fields] OR autisiclike[All Fields] OR autisim[All Fields] OR autisitc[All Fields] OR autisitcsubjects[All Fields] OR autism[All Fields] OR autism’[All Fields] OR autism’s[All Fields] OR autism1[All Fields] OR autism360[All Fields] OR autismaid1[All Fields] OR autismand[All Fields] OR autismate[All Fields] OR autismcare[All Fields] OR autismcenter[All Fields] OR autismcrc[All Fields] OR autismdata[All Fields] OR autisme[All Fields] OR autisme’[All Fields] OR autismeexpertise[All Fields] OR autismeforeningen[All Fields] OR 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autismstudiesnet[All Fields] OR autismstudynurseasu[All Fields] OR autismtherapies[All Fields] OR autismu[All Fields] OR autismul[All Fields] OR autismului[All Fields] OR autismus[All Fields] OR autismusbehandlung[All Fields] OR autismusforschung[All Fields] OR autismusspektrumstorungen[All Fields] OR autismussyndrom[All Fields] OR autismustherapiezentrum[All Fields] OR autismuszentrum[All Fields] OR autisn[All Fields] OR autisru[All Fields] OR autissier[All Fields] OR autissiodorensis[All Fields] OR autist[All Fields] OR autista[All Fields] OR autistacon[All Fields] OR autistas[All Fields] OR autiste[All Fields] OR autisten[All Fields] OR autistes[All Fields] OR autisti[All Fields] OR autistic[All Fields] OR autistic’[All Fields] OR autistic’s[All Fields] OR autistica [All Fields] OR autistical[All Fields] OR autistically[All Fields] OR autisticand[All Fields] OR autisticas[All Fields] OR autisticheskii[All Fields] OR autisticheskikh[All Fields] OR autisticheskogo[All Fields] OR autisticheskoi [All Fields] OR autisticheskom[All Fields] OR autistici[All Fields] OR autistickeho[All Fields] OR autistickych[All Fields] OR autisticlike[All Fields] OR autisticne[All Fields] OR autisticnog[All Fields] OR autisticnom[All Fields] OR autistico[All Fields] OR autisticos[All Fields] OR autistics[All Fields] OR autistics’[All Fields] OR autistiform[All Fields] OR autistique[All Fields] OR autistiques[All Fields] OR autistisch[All Fields] OR autistische [All Fields] OR autistischem[All Fields] OR autistischen[All Fields] OR autistischer[All Fields] OR autistisches[All Fields] OR autistischundisziplinierten[All Fields] OR autistisk[All Fields] OR autistiska[All Fields] OR autistiske[All Fields] OR autistism[All Fields] OR autististic[All Fields] OR autistm[All Fields] OR autistoid[All Fields] OR autists[All Fields] OR autisyn[All Fields])) OR asperger[All Fields]) OR (“autism spectrum disorder”[MeSH Terms] OR (“autism”[All Fields] AND “spectrum”[All Fields] AND “disorder”[All Fields]) OR “autism spectrum disorder”[All Fields])) OR (“Arthropod Struct Dev”[Journal] OR “Agron Sustain Dev”[Journal] OR “asd”[All Fields])) OR (“asperger syndrome”[MeSH Terms] OR (“asperger”[All Fields] AND “syndrome”[All Fields]) OR “asperger syndrome”[All Fields])) OR asperger’s[All Fields]) OR (asperger[All Fields] OR asperger’[All Fields] OR asperger’s[All Fields] OR asperger’s’[All Fields] OR asperger`s[All Fields] OR aspergera[All Fields] OR aspergere[All Fields] OR aspergerfoundation[All Fields] OR aspergerian[All Fields] OR aspergerillus[All Fields] OR aspergerin[All Fields] OR aspergerov[All Fields] OR aspergers[All Fields] OR aspergers’s[All Fields] OR aspergersyndroom[All Fields])) OR (“autistic disorder”[MeSH Terms] OR (“autistic”[All Fields] AND “disorder”[All Fields]) OR “autistic disorder”[All Fields])) OR (“autistic disorder”[MeSH Terms] OR (“autistic”[All Fields] AND “disorder”[All Fields]) OR “autistic disorder”[All Fields] OR “autistic”[All Fields])) AND (“1995/01/01”[PDAT]: “2020/12/31”[PDAT]) AND “humans”[MeSH Terms] AND English[lang]) AND ((“1995/01/01”[PDAT]: “2020/12/31”[PDAT]) AND “humans”[MeSH Terms] AND English[lang])
Web of Science	TOPIC: ((virtual reality) OR (virtual realit*) OR(virtual learning environment) OR (virtual learning environment*) OR (virtual-reality) OR (virtual-realit*) OR (VR) OR (virtual environment) OR (virtual environment*) OR (virtual world) OR (virtual world*) OR (virtual-world) OR (virtual-world*) OR (collaborative virtual learning environment*) OR (3d virtual worlds) OR (3d virtual world*) OR (MUVE) OR (CAVE) OR (head-mounted display)) AND TOPIC: ((autism) OR (autism*) OR (autistic) OR (autis*) OR (asperger) OR (autism spectrum disorder) OR (asd) OR (Asperger Syndrome) OR (aspergers) OR (Asperger*) OR (Autistic Disorder) OR (Autistic))
Scopus	(TITLE-ABS-KEY (virtual AND reality) OR TITLE-ABS-KEY (virtual AND realit*) OR TITLE-ABS-KEY (virtual AND learning AND environment) OR TITLE-ABS-KEY (virtual AND learning AND environment*) OR TITLE-ABS-KEY (virtual-reality) OR TITLE-ABS-KEY (virtual-reality*) OR TITLE-ABS-KEY (vr) OR TITLE-ABS-KEY (virtual AND environment) OR TITLE-ABS-KEY (virtual AND environment*) OR TITLE-ABS-KEY (virtual AND world) OR TITLE-ABS-KEY (virtual AND world*) OR TITLE-ABS-KEY (collaborative AND virtual AND learning AND environment*) OR TITLE-ABS-KEY (3d AND virtual AND worlds) OR TITLE-ABS-KEY (3d AND virtual AND world*) OR TITLE-ABS-KEY (muve) OR TITLE-ABS-KEY (cave) OR TITLE-ABS-KEY (head-mounted AND display) AND TITLE-ABS-KEY (autism) OR TITLE-ABS-KEY (autism*) OR TITLE-ABS-KEY (autistic) OR TITLE-ABS-KEY (autisti*) OR TITLE-ABS-KEY (asperger) OR TITLE-ABS-KEY (autism AND spectrum AND disorder) OR TITLE-ABS-KEY (asd) OR TITLE-ABS-KEY (asperger AND syndrome) OR TITLE-ABS-KEY (asperger*) OR TITLE-ABS-KEY (autistic AND disorder) OR TITLE-ABS-KEY (autistic)) AND PUBYEAR > 1994 AND (LIMIT-TO (LANGUAGE, “English”)) AND (LIMIT-TO (PUBSTAGE, “final”)) AND (LIMIT-TO (DOCTYPE, “ar”))

(*Continued*)

Appendix A (Continued).

Database	Search Query
IEEE Xplore	(((((“All Metadata”:virtual reality) OR “All Metadata”:virtual*) AND “All Metadata”:autism) OR “All Metadata”:asd) AND “All Metadata”:autism*)
ERIC	((virtual reality) OR (virtual realit*) OR (virtual learning environment) OR virtual learning environment*) OR (virtual-reality) OR (virtual-realit*) OR (VR) OR (virtual environment) OR (virtual environment*) OR (virtual world) OR (virtual world*) OR (virtual-world) OR (virtual-world*) OR (collaborative virtual learning environment*) OR (3d virtual worlds) OR (3d virtual world*) OR (MUVE) OR (CAVE) OR (head-mounted display)” AND “(autism) OR (autism*) OR (autistic) OR (autis*) OR (asperger) OR (autism spectrum disorder) OR (asd) OR (Asperger Syndrome) OR (asperger’s) OR (Asperger*) OR (Autistic Disorder) OR (Autistic)) AND ((autism) OR (autism*) OR (autistic) OR (autis*) OR (asperger) OR (autism spectrum disorder) OR (asd) OR (Asperger Syndrome) OR (asperger’s) OR (Asperger*) OR (Autistic Disorder) OR (Autistic))
Google Scholar	allintitle: virtual reality autism