Defining Virtual Reality (VR). Scoping Literature Review on VR Applications in Autism Research

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Virtual Reality (VR) systems are a sophisticated interplay of technology and human perception. VR systems share three main features: immersion, interaction, and a sense of presence. Many empirical studies have since recognized VR as an important therapeutic tool. Research in VR and psychology has increased exponentially over the last few decades and has been reviewed previously. In our review, we will examine VR use in autism research as an illustrative example to demonstrate a need for precise definitions. Three databases were chosen: Web of Science, PubMed and Google Scholar. 42 studies were analysed. Recommendations for future research have emerged from the reviewed literature, such as the need for larger sample sizes representing the entire autism spectrum and wider age ranges. The most substantial problem in the literature reviewed is the problem of definitions of VR. We describe the need for clear definitions of the equipment used and propose more refined terminology.

Highlights:

- Virtual Reality (VR) is a sophisticated interplay of technology and human perception.
- Autism is a neurodevelopmental condition characterised by social difficulties, repetitive/restrictive behaviours and sensory sensitivity.
- VR research in autism has grown exponentially over the last two decades.
- Our review evaluated 42 studies on this topic published between 2015 and 2020 and their demographic trends.
- Our main conclusion is that we need to reassess the use of the technical terminology in VR and autism research so that the level of immersion of a given technique is clearer.

Keywords: virtual reality, autism, review, definitions

1. Introduction

Virtual Reality (VR) is a term used to describe a range of technologies, including, but not limited to, virtual worlds (VW), massive multiplayer online role playing games (MMORPGs), virtual (collaborative) environments, cave automatic virtual environments (CAVE), static VR (using smartphones) and head mounted displays (HMDs) (Newbutt, Bradley & Conley, 2020). Jaron Lanier coined the term ‘Virtual Reality’ or ‘VR’ in the 1980s (Lanier, 2017). After an initial rise in the 1980s and 1990s, Virtual Reality use soon faded away due to limited availability of technology and high costs. Research mostly continued in the fields of engineering, aeronautics and visual perception (Sheridan, 1992; Robinett & Rolland, 1992). However, in 2014, start-up company Oculus was purchased by Facebook (BBC, 2014), and this marked a new dawn for Virtual Reality. The technology has now become cheaper and much more accessible. This has resulted in a broader interest in immersive technology, including augmented reality (AR) and mixed reality (MR).

Virtual Reality is as difficult to define as the experience itself. VR systems are a sophisticated interplay of technology and human perception. Merriam-Webster dictionary (n.d.) defines VR as ‘an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one’s actions partially determine what happens in the environment’. However, general understanding of VR is narrower and often refers to an artificial environment experienced through a variety of senses, which is created by a computer and accessed via a display, often a Head-Mounted Display (HMD) (Mandal, 2013). An HMD is a pair of large glasses strapped onto the head, which displays a virtual environment using two different images, one projected to each eye, creating the compelling illusion of a three-dimensional scene all around them. Alongside state-of-the-art graphics, a VR system usually incorporates one or more input devices (e.g. controllers, gloves or motion trackers) (Newbutt, Bradley & Conley, 2020). Virtual Reality system capabilities vary greatly

depending on the device capacity and the quality of the built three-dimensional world. However, all VR systems share three main features: immersion, interaction and a sense of presence (Alcaniz-Raya et al, 2020). Immersion refers to how well the system isolates the user from reality. Interaction allows the user to interact with objects in the virtual environment in real time. Immersion is inherently linked to hardware capabilities (Slater & Sanchez-Vives, 2016). A sense of presence is a consequence of immersion and interaction. It is the psychological feeling of being present in the virtual environment despite the awareness of not actually being there in the real world (Alcaniz-Raya et al, 2020). Virtual Reality systems provide highly immersive environments and safe, but realistic, scenarios. Over the last decade many areas of psychology have adapted this new technology to run easily controllable and ecologically valid experiments. In our review, we will examine VR use in autism research as an illustrative example to demonstrate a need for precise definitions.

Autism Spectrum Disorder (ASD)¹ is a neurodevelopmental condition characterised by social difficulties, repetitive/restrictive behaviours and sensory sensitivity (APA, 2013). It is estimated that at least 1% of the UK population is affected by the condition (NHS, 2016). The latest study by the Centre for Disease Control (CDC) suggests a prevalence close to 2% in the USA (Baio et al., 2018). Clinical heterogeneity is well established. Cognitive difficulties, delayed or atypical language production and atypical social development are just some of the many interrelated signs and symptoms associated with ASD (Miller, Wiederhold, Miller & Wiederhold, 2020).

One of the earliest descriptions of Virtual Reality in Autism was by Dorothy Strickland in 1997. Many empirical studies have since recognized VR as an important therapeutic tool (Kandalaf et al, 2013; Halabi et al, 2017; Wang & Reid, 2011). VR was introduced as a

¹ ASD, autism and individuals with autism will be used interchangeably in this paper. Recent research on neurodiversity and person-first vs. identity-first language, suggests this is an appropriate use of terminology (see Bury, Jellet, Spoor and Hedley (2020)).

beneficial tool, characterised by controllable stimuli, allowing the safe modification of the environment, consisting of primarily a visual and auditory world, and with the potential for individualised scenarios (Strickland, 1997). Stimuli could be introduced in a slow and regulated way, and with the frequent attentional difficulties in ASD, participants' focus could be maintained by a structured and adjustable environment. Moreover, participants could interact with the objects around them, knowing that they were in a simulated world. Autistic individuals have also been found to respond well to treatments and interventions provided by computers (Strickland, 1997; Maskey et al, 2014).

Research in Virtual Reality and psychology has increased exponentially over the last few decades and has been reviewed previously. Parsons' (2016) review concluded that VR is veridical (authentic and realistic) with strong ecological validity, stressing that exploration of different factors affecting the responses is required. VR is described as a 'bridge to the real world' and is potentially transformative for education, especially for autistic individuals (Parsons, 2016). Sense of presence, one of the key aspects of VR described earlier, is of key importance for ASD as it allows the authentic simulation of social situations. Valmaggia, Latif, Kempton and Rus-Calafell (2016) reviewed 24 studies between 2012-2015, before the second peak of interest in VR in 2016, and focused on VR training for autistic individuals and concluded it had potential for intervention and treatment in mental health settings. In 2017, Yi, Suk-Hyang and Min-Kyung (2017) reviewed the feasibility and appropriateness of VR in autism research in Korea. This example highlights the need for multi-cultural research. Bradley & Newbutt (2018) discussed the renewed interest in immersive technology and reviewed studies through an educational lens, where Thai & Nathan-Roberts (2018) found that the majority of studies in VR and autism focused on the improvement of social skills. Mesa-Gresa et al (2018) highlighted the need for publications outside psychiatry and included searches from the Web of Science database to expand the reach and include technologically

oriented publications. Unlike previous reviews, Mesa-Gresa et al (2018) found only moderate support for the effectiveness of VR-based treatments in autism. Most recently, Miller et al (2020) listed all studies from 1996 which included autistic participants and some form of Virtual Reality as a comprehensive overview of the emerging trends in the research.

All previous reviews have established that the majority of work in VR for autism is focused on social skills training and interventional aspects, selected samples are limited to small populations (mostly children) and the majority of studies are conducted in Western societies. Recommendations for more diverse samples and treatments are undoubtedly important, however there are other matters emerging in the recent literature, which have been highlighted previously but never examined in detail. Mandal (2013) identified that VR terminology has been misused since the first emergence of the technology in 1990s. Immersion, presence and interactivity distinguishes VR from other representational technologies and has become a niche area of its own. Mandal (2013) hinted at the issue of terminology before the second boom of VR in 2016. Slater and Sanchez-Vives (2016) also discussed this issue of terminology, especially as the hardware was becoming more commercially available with higher fidelity, increased resolution, reduced latency and higher framerates. The issue of what can be considered truly immersive has surfaced once again. Now, five years down the line we cannot deny that VR has found its way into psychology research. Studies are growing in numbers and it is a perfect time to re-evaluate our definitions of immersion and its dependence on the hardware.

The current review aims to assess research from the onset of the Virtual Reality “re-emergence” in 2015 until the end of 2020. We aim to identify the main topics still emerging from research published in academic journals, highlight recommendations for future research and, most importantly, evaluate the accuracy of terminology used to describe levels of immersion in VR.

We note here the important difference between the Virtual Reality Experiences (VREs) that a user or participant undergoes, and the technology used to achieve those experiences. It may be argued that we should be interested *only* in the VREs and not in the means by which they were achieved. Whilst it is possible to have VREs that do not utilise the capability of the hardware used, it is not possible for the VREs to exceed the capabilities of the hardware. Thus, our review will focus on the hardware used to determine the functional limits of the VRE being studied. We think that this technocentric approach is justified within the context of this review, but we do not think that it is the only taxonomic work required in order to improve and clarify the reporting of VR-related research.

2. Methods

The literature search was conducted at the end of October 2020. We used the principles of systematic review to find relevant literature (PRISMA guidelines) but did not perform a thorough systematic “analysis” as has been conducted by previous reviews (for example, Mesa-Gresa et al, 2018). Instead, we “scoped” the literature to identify the accuracy of terminology used to describe the level of immersion, which we then used to group studies into appropriate categories (for definition and guidance on scoping reviews see Munn et al, 2018).

Three databases were chosen: Web of Science, PubMed and Google Scholar. Web of Science includes a wide scope of papers throughout different science disciplines. PubMed focuses mostly on medical research, and Google Scholar includes a large variety of publications. Keywords used for the search were ‘Virtual Reality’ and ‘Autism’. “Asperger’s” and other associated conditions were excluded. Only the term ‘Virtual Reality’ was chosen, excluding other terminology such as ‘virtual environment’, ‘virtual world’ or ‘three-dimensional world’. We were interested in exploring how the technology used in each study is reflected in the

terminology. Many studies use VR in the title; however, the methodology used does not fully represent the level of immersion. ‘Autism’ returned searches, including terms like ‘ASD’ and ‘Autism Spectrum Disorders’, which were included in the final selection. The paper had to have both terms (‘Virtual Reality’ and ‘autism’) in the title.

The date range selected was from January, 2015, to October, 2020. The date range was chosen to review the most recent research on the topic and the year 2015 is a significant date for Virtual Reality technology because of the emergence of the developer kit for HTC Vive and pre-launch of Oculus Rift (BBC, 2014).

Figure 1. Flowchart showing how papers were identified and screened for eligibility.

The initial search of the two selected keywords returned 38k results in Google Scholar, 144 results in PubMed and 586 in Web of Science. Publications were further filtered to be in English, including only journal articles and removing any duplicates, patents, citations and conference abstracts/papers (Figure 1). After applying all our filters, we matched papers over all three databases to remove any duplicates. The remaining 50 papers were further assessed for relevance and the final 42 studies were included in our review.

3. Results

Full details of all 42 papers are listed in Table 1. The majority of publications were training (33.33%), intervention (21.43%) and empirical (21.34%) studies. The remaining were machine learning, pilot, feasibility and case studies.

The largest group of included studies were published in 2016 (29%) coinciding with Oculus Rift and HTC Vive becoming easily available to developers in 2015 and most researchers in 2016. The years immediately following the event, 2015 (7%), had fewer publications, probably because of the time it takes to get through the editorial process. 2016 (19%) saw a slight decline in publications, but in 2018 (17%) it was gaining a momentum reaching 8 publications in 2019 (19%) and 13 publications in 2020 (31%) (Figure 2). Fluctuating

numbers reflect variable trends in technology and business (Lang, 2020)

Figure 2. Descriptive Information on the 42 studies reviewed. A. Types of studies, B. Year of publication, C. Type of Virtual Reality used, D. Country where research was conducted.

A full list of the number of participants in each paper is given in Table 1. It ranges from case studies with only 1 participant (De Luca et al., 2019; Meindl et al., 2019) to larger studies of 51 (Parsons & Carlew, 2016) and 30 (Didehbani et al., 2016). Ghanovuni et al.'s (2018) paper assessed parents of children with ASD and clinicians rather than autistic individuals themselves. This study had one of the largest numbers of participants (63). Studies conducted in 2015-2018 had significantly less participants, mostly focusing on close observation of 3-10 individuals. Ip et al (2018) and Yvan & Ip (2018) identified the need for larger numbers of participants and recruited 72-94 autistic participants. Out of 13 studies published in 2020, only McCleery et al (2020) recruited a larger number of autistic individuals (n=60).

The mean age of autistic participants was 18.2 years with a higher proportion in the younger population (4-16 years). Studies with autistic participants of both genders included 70-80%

male participants, which reflects the current estimated sex ratio of 4:1 for diagnosed ASD (Loomes, Hull & Mandy, 2017). Increasing research suggests that the ratio is not truly reflective of the autistic population due to a potentially different phenotype of autism in females (Iyama-Kurycz, 2020). If this is correct, the majority of studies conducted on ASD to date, including this review, significantly under-represent females with the diagnosis.

The majority (53%) of studies were conducted in North America, mostly in the USA (see Table 1 for full breakdown). 36% were conducted in Europe, with a large portion of research in the UK and Spain. Studies conducted in Asia (mostly China and Hong Kong) made up 7% of the 42 studies reviewed. Australia (2%) and Africa (only 1 study) were under-represented in our sample. It is indicative of a need for research in a broader cultural context. Although the academic inequality presented here can be indicative of policies and research focus outside of authors' control.

Journals where research has been published were mostly focused on autism and associated conditions (67%) and only 33% of publications were published in journals on technical innovation. This balance has been tipped in favour of technological journals in 2019 and 2020, which points to an increasing trend for research into immersive technologies across the disciplines.

Figure 3. Virtual Reality equipment used. A. Desktop-VR; B. CAVE-VR; C. HMD-VR.

used in the abstract of the 42 studies. Note that the search terms ‘Virtual Reality’ and ‘autism’ were excluded from the word cloud as we know they would have the highest count and would have obscured the importance of other more informative terms. We were primarily interested in other themes emerging in the papers we have reviewed. Although word clouds are not a formal methodology generally used in reviews, we felt it highlighted some aspects of the literature not captured by the statistical figures. This method highlighted emerging themes, which could be subdivided into three categories: age of participants, purpose of the studies and types of studies.

‘Children’ and ‘Young’ were words used frequently, affirming the previously discussed average age of participants (Table 1). Mesa-Gresa et al (2018) reviewed 31 papers between 2010 and 2018 focusing on children and young adults. Mesa-Gresa et al (2018) identified social skills, emotions, daily living activities, communication and cognitive training as the main points of discussion. In our review a large number of studies focused on children (4-12 years) or adolescents (12-16 years). This can be explained by the generally accepted view that many autistic characteristics develop early in life and early intervention is crucial.

However, the long-term effects of VR and how it might impact cognitive development are unclear. Children have been found to respond positively to VR (Foley & Maddison, 2010; Parsons & Cobb, 2011; Parson et al, 2009), but there are, as yet, no longitudinal studies to evaluate if this new technology is beneficial in the long term.

Collaborative interactions have featured frequently in the literature we reviewed. Ke & Lee (2016) explored a collaborative design and problem-solving task, where children (8-10 years old, 2 ASD + 1 NT) were asked to work together to design a new city in Japan after an earthquake. Wallace, Parsons & Banley (2016) investigated autistic children’s communication with computer avatars, raising the question of what proportion of improvements can be attributed to the VR medium itself in the collaborative scenarios.

The aims of the studies were indicated by words such as ‘Social’, ‘Skills’, ‘CBT’, ‘Training’ and ‘Exposure’. A clear focus emerged on the social aspects of autism and the need to improve these skills using standard exposure and CBT techniques. Smith et al (2014, 2015) investigated the effectiveness of job interview training, Didehbani et al (2016) looked into social cognition training, Miller et al (2019) tested air travel training, Meindl et al (2019) explored exposure therapy in the treatment of blood draw phobia and Maskey et al (2014, 2019, 2019) analysed the effectiveness of Virtual Reality CBT (Cognitive Behaviour Therapy). All studies highlighted the benefits of using Virtual Reality in exposure and training sessions to enhance social skills in autism.

Virtual Reality enables participants to experience an everyday context in a safe, controlled and supportive environment. The supportive environment enables active participation. Sessions can be repeated multiple times and at a pace suitable for each individual. VR can also be highly personalised for each participant; however, this can be time consuming to construct. Maskey et al (2014, 2019a, 2019b) were the only studies reviewed which took time to adapt each session to individual participants. For example, an autistic child with a phobia of pigeons was first exposed to a square where pigeons are likely to be. Then, a single pigeon was introduced and, depending on the child’s reaction and ability to control their emotions, the number of pigeons gradually increased. Maskey et al’s (2014, 2019a, 2019b) trials have proven to be successful in reducing specific phobias in ASD.

Types of studies were described by the words ‘Treatment’, ‘Therapy’, ‘Intervention’ and ‘Effectiveness’. With anxiety as a key co-occurring condition in ASD (Maskey et al, 2014) it is not surprising that many studies seek to address it. The goal seems to be a direct and marketable application for healthcare and education. Autistic individuals often struggle with dual tasking and response inhibition, which means that everyday tasks can be challenging. Cox et al (2017) investigated how new VR and eye-tracking technology can improve driving

performance, and Smith et al (2014, 2015) discussed aspects of job interview training. Where Cox et al (2017) focused mainly on improvements of working memory, Smith et al (2014, 2015) looked into improvements in social skills and communication. Moreover, Maskey et al's (2014, 2019a, 2019b) studies have proven to be so successful that their intervention is now being considered as a treatment by NHS UK (the National Health Service in the United Kingdom).

All the words highlighted here were counted 9-23 times over 42 abstracts. On the other hand, many words were rarely used. 'Real-life', 'Objective' and 'Standardized' were each used only once, highlighting a clear need for a more generalizable outcome. Due to the novelty of Virtual Reality it is a very attractive technique to use, but this means that the majority of current studies are exploratory.

Only a handful of studies have looked into aspects of executive function. Forbes, Pan & Hamilton (2016) explored mimicry and embodied experiences, and Parsons & Carlew (2016) tested the effects of inhibition in a Stroop task. Distractions seemed to have had more effect in the immersive virtual world rather than in computer-based tests. For example, Meindl et al (2019) used a distraction technique in VR to combat blood draw phobia. There appears to be an emerging link between cognitive differences and social skills in ASD.

Progress has been made in the area of neuroscience and virtual reality. Neural mechanisms have been investigated by Yang et al (2017, 2018). The researchers identified neuroimaging-based predictive biomarkers for treatment effectiveness. A review by Riva, Wiederhold and Mantovani (2019) discussed twenty-five articles of successful treatment in anxiety disorders, eating disorders and pain management. Forlim et al (2019) found that VR training improves brain connectivity functionally and structurally. Maggio et al (2019) also found positive

effects of VR in cognitive rehabilitation in various neurological conditions. Thus, there seems to be a clear need for additional research into the effect of VR on brain function in ASD.

Table 1. List of all publications discussed in the systematic review in alphabetical of authorship. Authors, Year and Title of the papers are listed along side the journal they were published in, number, age and gender of participants, VR type and other diagnostic measures used, and country of research.

Author(s)	Year	Title	Journal	Number of participants	Age of participants	Gender of participants	VR type	Measures used **	Country of research	Type of study
*Yang et al	2017	Brain Responses to biological motion predict treatment outcome in young adults with Autism receiving virtual reality social cognition training: preliminary findings	Behaviour Research & Therapy	17 ASD	mean 22.5	2 females	desktop VR	fMRI, SRS-2	USA	Training
*Yang et al	2018	Neural Mechanisms of Behavioural Change in Young adults with High Functioning Autism receiving virtual reality cognitive training: a pilot study	Autism Research	17 ASD	mean 22.5	2 females	desktop VR	fMRI, SRS-2	USA	Training
Cox et al	2017	Can youth with autism spectrum disorder use Virtual reality driving simulation training to evaluate and improve driving performance? An exploratory study	JADD	51 ASD - 28 - 23- 18	mean 17.96	78% males	210 degrees VR projector, CAVE like	Eye tracking, standard driving proficiency assessment	USA	Training
De Luca et al	2019	Innovative use of virtual reality in autism spectrum disorder: a case study	Applied Neuropsychology: Child	1 ASD + caregiver	16y	males	desktop VR	RCI, RMT, MTCM, VMI, QSG, GARS	Europe (Italy)	Case study
Didehbani et al	2016	Virtual Reality Social Cognition Training for children with high functioning autism	Computers in Human Behaviour	30 ASD	7-16y	4 females	desktop VR	WASI, NEPSY	USA	Training
Dixon et al	2019	Evaluation of an Immersive Virtual Reality Safety Training Used to Teach Pedestrian Skills to Children With Autism Spectrum Disorder	Behavior Analysis in Practice	3 ASD	4-10y	males	Oculus Rift	Treatment response	USA	Training

Fitzgerald et al	2018	Comparing the effectiveness of virtual reality and video modelling as an intervention strategy for individuals with ASD: a brief report	Developmental Neurorehabilitation	2 ASD	25 & 31	males	Oculus Rift	WISC-II, CARS, accuracy	Australia	Intervention
Forbes, Pan & Hamilton	2016	Reduced mimicry to Virtual Reality avatars in Autism Spectrum Disorder	JADD	25 NT, 26 ASD	mean 27.5 NT, 28.3 ASD	6 female NT, 4 female ASD	desktop VR	Motion capture, WAIS-III, ADOS - G	UK	Empirical
Ghanovuni et al	2018	Social stories for children with Autism Spectrum Disorder: Validating the content of a Virtual Reality program	JADD	63 parents & clinicians	25-65 clinicians, 30-59 parents	2 out of 24 male in clinicians, 2 in 39 parents male	desktop VR	Emotion Type and Intensity measured	USA, Canada	Training
Halabi et al	2017	Design of Immersive Virtual Reality System to Improve Communication Skills in Individuals with Autism	International Journal of Emerging Technology	3ASD; 7NT	4-6y; 9-12y	NA	CAVE VR	User satisfaction questionnaire	Egypt, Qatar	Empirical
Hu and Han	2019	Effects of gesture-based match-to-sample instruction via virtual reality technology for Chinese students with autism spectrum disorders	JIDD (Journal of Intellectual and Developmental Disability)	3 ASD	6-7y	3 male	Leap Motion VR	Task engagement, social validity	China	Intervention
Ip et al	2018	Enhance emotional and social adaptation skills for children with autism spectrum disorder: A virtual reality enabled approach	Computers and Education	94ASD	6-12y	86 male	CAVE VR	RPM, CAST, Faces test (Baron Cohen et al, 1997), Eyes test (Baron-Cohen et al, 2001), PEP-3	Hong Kong	Training
Jacques et al	2018	The "Decoding of Social Interactions in Virtual Reality" Tasks for Autism Spectrum People: Development of an Intervention Protocol and Pilot Testing	Annual Review of Cybertherapy and Telemedicine	3 ASD	NA	males	CAVE VR	Perception of social decoding and social skills (OPI), Social Intervention Self Assessment (SISST)	Canada	Intervention, Pilot
Johnson, Egermann and Kearney	2019	Measuring the Behavioral Response to Spatial Audio within a Multi-Modal Virtual Reality Environment in Children with Autism	Applied Sciences	27 ASD	mean 14y	males	Oculus Rift	Satisfaction, interaction time and anxiety levels	UK	Training

		Spectrum Disorder								
Johnson, Egermann and Kearney	2020	SoundFields: A Virtual Reality Game Designed to Address Auditory Hypersensitivity in Individuals with Autism Spectrum Disorder	Applied Sciences	6 ASD	mean 17.7y	4 male	Oculus Rift	Satisfaction, interaction time and anxiety levels	UK	Training
Ke & Lee	2016	Virtual Reality based collaborative design by children with high functioning autism: design based feasibility, identity and norm construction	Interactive Learning Environments	2 ASD + NT	8-10y	2 females	desktop VR	Social felxibility, Identity expression, Norm construction	USA	Feasibility Trial
Ke et al	2015	Experience of Adult Facilitators in a Virtual-Reality-Based Social Interaction Program for Children With Autism	Journal of Special Education	5 ASD	9-10y	NA	desktop VR	Socialisation	USA	Empirical
Ke, Moon and Sokolikj	2020	Virtual Reality-Based Social Skills Training for Children With Autism Spectrum Disorder	Journal of Special Education Technology	7 ASD	11-14y	6 male	HMD	SCQ, SSQ	USA	Training
Lahiri et al	2015	A physiologically informed virtual reality based social communication system for individuals with autism	JADD	8 ASD	15.88mean	?	desktop VR	ADOS-G, SRS, SCQ, PPVT-III, ADI-R	India, USA	Empirical
Lorenzo et al	2016	Design and application of an immersive virtual reality system to enhance emotional skills for children with autism spectrum disorders	Computers and Education	17-24 ASD	7-12y	NA	CAVE VR	Success of intervention	Spain	Intervention
Malihi et al	2020	Data-Driven Discovery of Predictors of Virtual Reality Safety and Sense of Presence for Children With Autism Spectrum Disorder: A Pilot Study	Frontiers in psychiatry	35 ASD	mean 13y	10 female	Oculus Rift	ADOS, ADI-R, SCQ, WASI	Canada	Pilot

Malihi et al	2020	Short report: Evaluating the safety and usability of head-mounted virtual reality compared to monitor-displayed video for children with autism spectrum disorder	Autism	35 ASD	mean 13y	25 male	desktop VR, Oculus Rift	IQR, SCQ, SCARED	Canada	Feasibility Trial
Maskey et al	2019	A randomised controlled feasibility trial of immersive Virtual Reality treatment with cognitive behaviour therapy for specific phobias in young people with Autism Spectrum Disorder	JADD	32	8-14y	3 female + 13 male	CAVE system (Blue Room)	ADIS, CGAS, SCQ, VABS, SCAS, FSSC-R, CAPE, Attendance	UK	Feasibility Trial
Maskey et al	2019	An intervention for fears and phobias in young people with ASD using flat screen computer delivered virtual reality and cognitive behavioural therapy	Research in ASD	8 ASD	8-12y	males	desktop VR	SCAS-P & C, Target behaviour and confidence ratings	UK	Intervention
McCleery et al	2020	Safety and feasibility of an immersive virtual reality intervention program for teaching police interaction skills to adolescents and adults with autism	Autism Research	60ASD	12-38y	52 male	Static VR	SRS-2, WASI-II, SCQ, AQ, sensory profile	USA	Intervention
Meindl et al	2019	Reducing blood draw phobia in an adult with Autism spectrum disorder using low-cost virtual reality exposure therapy	JARID (Journal of Applied Research in Intellectual Disabilities)	1 ASD	26	1 male	Static VR (iPhone + Tzumi Dream Vision Headset)	Effectiveness assessed	USA	Intervention
Miller et al	2020	Virtual Reality Air Travel Training with children on Autism Spectrum: a preliminary report	Cyberpsychology, Behaviour and Social Networking	5 ASD	4-8y	1 female	Static VR (iPhone + Cardbox)	Air Travel Questionnaire	USA	Intervention
Moon and Ke	2019	Exploring the treatment integrity of virtual reality-based social skills training for children with high-functioning autism	Interactive Learning Environments	15 ASD	10-14y	13 male	desktop VR	Jaccard Similarity Coefficient (JI) (Loh & Shang, 2014)	USA	Training

Moon, Ke and Sokolikj	2020	Automatic assessment of cognitive and emotional states in virtual reality-based flexibility training for four adolescents with autism	British Journal of Educational Technology	4 ASD	13-19y	males	desktop VR	GARS-3	USA	Intervention
Newbut, Bradley and Conley	2020	Using Virtual Reality Head-Mounted Displays in Schools with Autistic Children: Views, Experiences, and Future Directions	Cyberpsychology, Behaviour and Social Networking	31 ASD	mean 12y	28 male	HTC Vive, ClassVR and Google Cardboard	User satisfaction questionnaire	UK	Empirical
Newbutt et al	2016	Brief report: a pilot study of the use of virtual reality headset in autism population	JADD	29 ASD	NA	22 M	Oculus Rift	WASI, ITC-SoPI	UK	Pilot
Newbutt et al	2016	The potential of virtual reality technologies to support people with an autism condition: A case study of acceptance, presence and negative effects	Annual Review of Cybertherapy and Telemedicine	29ASD; 11 ASD	mean 32.03y; mean 29.77y	76%male; 91% male	Oculus Rift	Spatial presence and engagement	UK, USA	Case study
Parish-Morris et al	2018	Immersive Virtual Reality to Improve Police Interaction Skills in Adolescents and Adults with Autism Spectrum Disorder: Preliminary Results of a Phase I Feasibility and Safety Trial	Annual Review of Cybertherapy and Telemedicine	28 ASD	mean 16.34y	males	Static VR	WASI-II, SCQ, AQ, System usability scale	USA	Feasibility Trial
Parsons & Carlew	2016	Bimodal Virtual Reality Stroop for assessing distractor inhibition in Autism Spectrum Disorder	JADD	52 NT; 8 ASD + 10NT	mean 20.37, 22.88	78% female; 2 + 4 female	desktop VR	WASI-II, WTAR, D-KEFS, ANAM Stroop, Virtual Stroop,	USA	Empirical
Alcaniz-Raya et al	2020	Application of Supervised Machine Learning for Behavioral Biomarkers of Autism Spectrum Disorder Based on Electrodermal Activity and Virtual Reality	Frontiers in Human Neuroscience	23 ASD; 30 NT	4-7y	NA	CAVE-VR	ADI-R, ADOS-2	Spain	Machine Learning
Alcaniz-Raya et al	2020	Machine Learning and Virtual Reality on Body Movements' Behaviors to Classify Children with Autism	Journal of Clinical Medicine	24 ASD; 25 NT	4-7y	21 male; 16 male	CAVE-VR	ADOS-2, ADI-R	Spain	Machine Learning

		Spectrum Disorder								
Simoes et al	2020	Virtual Reality Immersion Rescales Regulation of Interpersonal Distance in Controls but not in Autism Spectrum Disorder	JADD	25ASD; 23 NT	12-13y	23 male; 22 male	Oculus Rift	Stop Distance Paradigm (Gessaroli et al, 2013)	Portugal	Empirical
Smith et al	2015	Brief Report: Vocational outcomes for young adults with Autism Spectrum Disorders at six months after Virtual Reality job interview training	JADD	23 ASD	18-31y	75% male	desktop VR	SRS-2, RBANS, BLERT,	USA	Training
Smith et al	2020	Using community-engaged methods to adapt virtual reality job-interview training for transition-age youth on the autism spectrum	Research in Autism Spectrum Disorders	20 ASD; 21 carers	16-21y; 23-65y	NA	desktop VR	VR-JIT assessment	USA	Training
Valori et al	2020	Sensorimotor Research Utilising Immersive Virtual Reality: A Pilot Study with Children and Adults with Autism Spectrum Disorders	Brain Sciences	9ASD	8-13y; 23-39y	males	Oculus Gear VR + Samsung smartphone	Individual differences	Italy	Empirical
Wallace, Parsons & Bailey	2016	Self-reported sense of presence and responses to social stimuli by adolescents with Autism Spectrum Disorder in a collaborative visual reality environment	JIDD (Journal of Intellectual and Developmental Disability)	10 ASD, 10 NT	12-16y; 14-16y	1 female; 2 female	desktop VR	ITC-SoPI, SAQ, Facial expression recognition	UK, Canada	Empirical
Yuan and Ip	2018	Using virtual reality to train emotional and social skills in children with autism spectrum disorder	London Journal of primary care	72 ASD	mean 106.3 months	64 male	CAVE VR	PEP-3	Hong Kong	Training

*Yang et al (2017) and Yang et al (2018) describe the same study, however, it has been published in two separate journals.

**Table of abbreviations for the measurements is presented below.

Abbreviation	Full Title	Reference
ADI-R	Autism Diagnostic Interview - Revised	Rutter et al, 2003
ADOS	Autism Diagnostic Observation Schedule	Lord et al, 2000
ANAM	Automated Neuropsychological Assessment Metrics	Johnson et al, 2008
D-KEFS	Delis-Kaplan Executive Function Syste,	Delis et al, 2001
GARS	Gilliam Autism Rating Scale	Gilliam, 2006
MTCM	Modified Little Bell Test	Biancardi & Stoppa, 1997
PPVT-III	Peabody Picture Vocabulary Test	Dunn & Dunn, 1997
RMT	Raven's Matrices Test	Raven & Court, 1998
SCQ	Social Communication Questionnaire	Rutter et al, 2003
SRS	Social Responsiveness Scale	Constantino et al, 2003
VMI	Developmental test of Visual Motor Integration	Cummings et al, 2003
WASI	Wechsler Test	Taylor, 1999

4. Discussion

The aim of our systematic review was to analyse the most recent studies on Virtual Reality and Autism and establish the accuracy of terminology used to describe the level of immersion. We have chosen journal articles from 2015 onwards and reviewed the aims, number and age of participants, country and year of publication, and type of technology used. A comprehensive summary of the 42 papers reviewed is available in Table 1.

Several recommendations for future research have emerged from the reviewed literature. The sample size varied from case studies to 94 participants, however, the sample size was often small. Recruiting willing participants with ASD is often challenging and the majority of literature is focused on autistic individuals with skills similar to their neurotypical counterparts. Non-verbal autistics or individuals with intellectual disabilities are therefore under-represented in this research, as in many other areas of autism research (Stedman et al, 2019). Additional questions also emerge when a new technology is introduced. Studies included in our review did not highlight any major health and safety concerns regarding autistic participants, however, as this large population is under-represented it is still unclear how generalisable these claims are. Future studies should seek to include samples representative of the entire autism spectrum.

The ages of participants have also been fairly limited (average age 18.2 years). Without a doubt research in early development of ASD and prevention is important, however, there are many aspects of the condition which can be explored in the older autistic population (i.e. over 30 years of age). Recent research has expressed concern about older autistic individuals who rely heavily on their carers (Sonido et al, 2019; Marston & Samuels, 2019; Tse, 2019). Their future can often be uncertain and challenging when carers are unable to continue their role. A further exploration of the older autistic population can reveal possible applications of VR in

alleviating the strain of caring for oneself. In addition, exploring longitudinal outcomes of VR effects on cognitive development and decline, could illuminate whether the intervention and training effects remain.

Publications in technology-oriented journals were limited. Over 50% of journals in the sample were autism-focused. Mesa-Gresa et al (2018) identified this issue previously and our literature search some years later did not find much progress despite previous recommendations. Interdisciplinary and collaborative projects using VR in psychology are expanding. Further research should engage a wider audience.

A large proportion of the research exploring how VR can be used for autistic populations focuses on intervention and training. Over 50% of the studies focused on social aspects of autism. Although, autism is often characterised by difficulties with social interactions, it is just one part of the presentation. Sensory and sensorimotor difficulties and repetitive behaviours are also important facets of the condition; however, they appear to be understudied using VR. Recently, several researchers have investigated the sensory sensitivities associated with autism. Sensory processing is affected in over 90% of autistic children and it refers to the ability to capture and integrate complex information from the senses (Alcaniz-Raya et al, 2020). Valori et al (2020) found, using VR, that when learning new movements autistic children are less influenced by visual feedback and prefer proprioceptive feedback. Recent research has adapted VR for controllable stimulus input and safe tracking of training and assessment of learning in autistic children.

Figure 5. Virtual Reality definitions.

Finally, the most substantial problem in the literature reviewed is the problem of definitions of the level of immersion in VR. As briefly discussed earlier, there have been multiple types of VR technology used in the 42 reviewed studies. Levels of immersion in VR systems have been debated since Jaron Lanier first coined the term in 1980s. VR is different from other forms of human-computer interaction as users actively participate in the virtual world rather than observe it (Slater & Sanchez-Vives, 2016). When VR technology was limited - definitions were easier. Ivan Sutherland's Sword of Damocles in 1965 was one of the first versions of the HMD, although less sophisticated than its successors (Sutherland, 1965). VR has undergone many changes since the 1960s, and up until recently the level of immersion of the systems was inherently linked to its technological capabilities.

As demand for interactive VR systems grew, new versions of the original technology emerged and a once-simple definition became problematic. Although the quest for definitions was mentioned several times, it never reached the realms of academia. Mandal (2013) started sub-dividing technology based on the levels of immersion. Non-immersive systems, such as

Desktop VR, were described as low level and did not require any special device. This simplicity might have been the reason for the success of this methodology in research. Semi-interactive systems were described as LCD shutter glasses, which provided higher levels of immersion, but did not normally support interactive input/output. And finally, immersive systems were predominantly described as a HMD with stereoscopic view, position and location tracking (Mandal, 2013).

Industry and academia have been striving for clearer and unified definitions of immersion levels for decades. Several different definitions have emerged in other areas of VR research. Based on our literature search we argue that VR use in autism research is a perfect place to start implementing new definitions, which describe technology and the level of immersion more accurately. We build on Mandal's (2013) terminology and include some of the more recent developments as well as the concept of degrees of freedom (DOF).

Therefore, the technology used can be subdivided into two categories - Fully and Partially Immersive (Figure 5). Fully Immersive technology can be further subdivided by the degrees of freedom. Degrees of freedom (DOF) refers to the number of ways the user can move in the three-dimensional space (Figure 6). Three degrees of freedom (3 DOF) allows rotational movement around the x,y and z axes whilst remaining static, whereas six degrees of freedom (6 DOF) also allows for dynamic translational movement along those three axes (left or right, up and down). Fully Immersive 6 DOF technology is here referred to as HMD-VR (Head Mounted Display Virtual Reality) which allows for full immersion and movement in the virtual space. Only 27% percent (half of these in 2020) studies used HMD-VR (mostly Oculus Rift (2016)). If less than a third of papers using VR are using the paradigm form of the technology, then there is a high risk of miscommunication about what VR is capable of.

Figure 6. Degrees of Freedom (figure adapted from [virtualspeech.com](https://www.virtualspeech.com))

Fully Immersive 3 DOF technology (Figure 5) will be called S-VR (Static Virtual Reality). It has a limited scope for movement and generally includes a headset which presents a 360-degree view. Interaction with the virtual world is limited, and natural movement through the virtual space is not possible. Hence, we call it *static*. Examples of S-VR are Google Cardboard (2014) and Oculus Go (2018). The term ‘static’ once referred uniquely to 3-DOF VR headsets, and as of 2021 most static VR headsets remain 3-DOF. That makes ‘static’ a rival term to be used to pick out this class of headsets. There exists a notable exception, however, in the Oculus Quest line of headsets which allow dynamic VR experiences without a PC. With more 6-DOF static headsets anticipated in the future, it would be short-sighted to use ‘static’ here when it is the functional aspect of being static that is most relevant to the research methods and outcomes we are interested in..

Partial immersion VR is cheaper and easier to set up, however, the full immersion and sense of presence cannot be achieved. Here we have subdivided this category into three and six degrees of freedom in order to have an analogous comparison of the equipment used. Partial

Immersion 6-DOF technology is C-VR (Cave Virtual Reality) and is a set space, often a room, where the virtual world is projected onto the walls or 180-360 degree screen. Whilst C-VR improves immersion due to the wide field of view, the visibility of the real-world body offsets this, as interactivity is a key contributor to immersion. Participants are often allowed to move around the room; however, the experience is only partially immersive due to the limited physical interaction with the surroundings.

Partial Immersion 3-DOF technology will be referred to as D-VR (Desktop VR) and it encompasses all desktop-based experiments. It is the least immersive type of equipment discussed; however, it seems to be most commonly used in the studies we have reviewed (39%). Participants' interaction is restricted, and they can often respond just by using a controller or a keyboard whilst viewing the stimuli on the computer screen.

Although, there is nothing fundamentally wrong with any of the methodology described, advancements in headset technology mean that there is now a significant stratification in terms of the immersive power of equipment referred to as "VR". This suggests that there is a need for new distinctions in how we refer to the equipment used. HMDs are now dominating the Virtual Reality market and research should reflect it accordingly. Readers looking for research involving HMD's may feel misled disappointed, to learn that despite the use of Virtual Reality in the title and description of the studies the equipment used is often a desktop computer. Moreover, VR itself comes with additional terminology attached, such as augmented reality (AR), mixed reality (MR) and extended reality (XR), which are outside of the scope of this paper. The precise nature of scientific research requires a revised set of definitions so that what VR hardware is used is clearer in future experiments.

Limitations

An exponential increase in the VR literature is one of the key limitations of our study. Since 2019 at least a dozen new papers have emerged on VR and autism. This great increase in publications poses a challenge for any future reviews on the most recent developments.

Innovations in VR and associated fields are rapid and research needs to adapt. The Oculus Rift (2016) is used in the majority of the studies we have reviewed and is no longer the state-of-the-art equipment, and at least two new models have been introduced and tested already.

In 2020 alone, the use of HMD-VR in published research doubled and the term ‘immersive’ was used to describe VR in the majority of the studies reviewed. Interestingly, although 2015/16 is often thought to be the time when the HMD revolution spurred more research, the majority of the studies reviewed show that the equipment most commonly used was desktop VR. Consequently, the real driver might be game engines, such as Unity (2005) and Unreal (1998) launching powerful and easily accessible (i.e. cheap or free) ways of authoring graphically sophisticated, interactive, experiences for both desktop VR and HMD-VR.

Conclusion

Each generation of these new devices brings significant improvements in the size and design of the equipment, user interface and resolution. During 2020 the Covid-19 pandemic has resulted in knowledge exchange in academia being reshaped. Conferences have moved online allowing for more rapid information transfer. Therefore, the research and terminology used are in constant state of metamorphosis. We hope that our review is a first step towards more robust taxonomy and a beginning of a fruitful discussion.

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