Research in Autism Spectrum Disorders 117 (2024) 102453

Contents lists available at ScienceDirect

Research in Autism Spectrum Disorders

journal homepage: www.elsevier.com/locate/rasd

CAVE automatic virtual environment technology to enhance social participation of autistic people: A classification and literature review

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ARTICLE INFO

Keywords:
Autism Spectrum Disorder
CAVE Automatic Virtual Environment
Blue room
Magic room
Immersive room
Virtual Reality
Social skills
Social participation
Immersive inclusive leisure

ABSTRACT

CAVE technology enables multi-participant experiences without head-mounted displays, accommodating the sensory sensitivities of autistic people and helping to enhance their social participation in the community. To date, recent studies have primarily identified therapeutic uses, without focusing on the technology's recreational applications. To address this gap in the literature, our study aims to explore how CAVE technology can support the social participation of autistic people. This study was developed following the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA 2020) protocol to ensure a robust and rigorous SLR. Results show 1) That there are different types of CAVE technology with numerous potential benefits for autistic people multi-participant engagement, sensory comfort, and customizable learning; 2) That CAVE technologies can enable the development of different social skills distinguishing personal emotions or understanding the intentions of others and adapting to the context. 3) Cost, technical complexity, space requirement, mobility, and learning curve are some of the barriers preventing this technology from being widely used in community or school organizations. In conclusion, this study suggests that CAVE technology can enhance social skills in autistic people and holds promise for innovative and inclusive leisure pursuits tailored for autism inclusion.

1. Introduction

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition in which each autistic person may experience different levels of challenges in social communication/interaction and engage in repetitive patterns of behaviour, interests or activities (American Psychiatric Association, 2013). The fifth version of the diagnostic manual, DSM5, included sensory issues as one of four subtypes of repetitive/restricted behaviours (Grapel et al., 2015) In this paper, the terms 'autistic person' or 'autistic child' are used instead of 'person or child with ASD' in order to respect the preference of a majority of autistic people (Kenny et al., 2016) and move away from a capacitive language that would define autism as an illness (Bottema-Beutel et al., 2021). Autistic people have a wide

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https://doi.org/10.1016/j.rasd.2024.102453
Received 11 December 2023; Received in revised form 25 May 2024; Accepted 18 June 2024

Nomenclature

AR	augmented reality.
ASD	autism spectrum disorder.
CAVE	recursive definition of CAVE automatic virtual environment.
CPI	perception of social skills.
CPS	perception of social cues.
DD	development disorder.
DP	direct projection.
DSM-5	Diagnostic and Statistical Manual of Mental Disorders, 5th edition.
ES	exploratory study to test hypotheses or materials.
F	female.
HFA	high-functioning autism.
HMD	head-mounted display.
IP	indirect projection.
IQ	intellectual quotient.
ITC-SOPI	Sense of Presence Inventory.
IVE	immersive virtual environment.
IVR	immersive virtual reality.
L	longitudinal study resulting from the follow-up of a cohort.
M	male.
MR	mixed reality.
N	total sample.
n	subsample.
OD	other disabilities.
PEP-3	Psychoeducational Profile, 3rd edition.
TD	typically developing person.
VR	virtual reality.
XP	experimental study with control group and controlled parameters.
XPC	experimental case without control group and repeated outcomes.
XR	extended reality.

variety of strengths, abilities and impairments not yet fully understood. This combination makes each individual unique and often hard to comprehend and support. This has a major impact on their social participation (Taheri et al., 2016) and on the daily lives of their families (Karst & Van Hecke, 2012; Ooi et al., 2016). Nevertheless, we believe that in an inclusive society, all children and their families should have access to the same activities and have opportunities to participate and interact with members of their community. While personal factors related to autism are recognised as having an impact on social participation, environmental factors are also well documented as playing a role (King et al., 2003, 2006; Tonkin et al., 2014).

The limited availability of adapted activities, materials and services, coupled with inadequate guidance and support, negative social attitudes, and constrained financial resources significantly hinder opportunities for autistic children to engage in inclusive settings. Consequently, these barriers not only restrict the practice and development of social skills with peers, but also exacerbate individual challenges. The situation is even worse for children with cognitive disabilities and those with behavioural problems as they have fewer interactions with their peers (Geisthardt et al., 2002). Despite the fact that social participation and leisure activities are a fundamental right, they also have a positive impact on the quality of life of children and families (Carr, 2004; Coyl-Shepherd & Hanlon, 2013; Menear & Neumeier, 2015). Lack of participation leaves autistic people vulnerable to further social and psychological difficulties (Kawachi & Berkman, 2001). Studies consistently show reduced activity participation among autistic children when compared to allistic peers (generally called typically developing (TD) individuals) (Askari et al., 2015).

Families of young autistic children also report engaging less frequently in leisure activities compared to families of allistic children (Settle, 2016) and experience less satisfaction (Walton, 2019). Social participation is defined as a social phenomenon resulting from a complex process involving the ability to make friends, participate in community activities, engage in leisure and play (Koller et al., 2018). To foster an inclusive society, it is crucial to provide community activities that bring together all its members, including families, while valuing and embracing their diversity. Additionally, it is important to prioritise support for the development of individual competencies that enable active participation. For autistic children, this means, among other things, developing new participatory leisure activities that address their sensory, emotional and social needs while facilitating interaction, and enhancing their communication, emotional regulation and social skills.

As described by Mosher and Carreon (2021), immersive technology strongly motivates autistic students to learn and develop new skills. These technologies offer exciting opportunities to create engaging and interactive leisure experiences for individuals of all abilities level. Different types of immersive technologies can be used to promote skill development and social participation. Augmented reality (AR), Virtual Reality (VR), Mixed Reality (MR) and Extended Reality (XR) allow users to experience a sense of immersion and presence. Immersion is the degree of experience that VR simulates, thus bringing a strong feeling of presence, i.e. a psychological and perceptual state that gives the feeling of being there (Slater et al., 1996). According to the reality-virtuality continuum of Milgram and Kishino (1994), AR is an integral part of MR, adding virtual objects to actual reality (Van Krevelen & Poelman, 2010). MR is defined as a hybrid reality between the real and virtual worlds. Their combination allows the creation of new environments displayed in real time with physical and digital objects (Rebbani et al., 2021). XR is an 'extended' form of MR where reality is completely replaced by virtuality. A recent study prefers the term xReality (Rebbani et al., 2021). Of all these immersive technologies, IVR has become more widespread in recent years because it has become more affordable and accessible, unlike conventional tools. What is more, the fully immersive nature of VR takes the experience to the next level.

As described by Parsons and Mitchell (2002), VR has several properties that make it useful and highly motivating for autistic people. In VR activities, users can control their participation; the interactivity does not need to be face-to-face; the complexity of the interactivity can be modulated; behaviours and responses can be practised in an environment close to the real world without fear or stress. Fully immersive VR can be defined as a complex system capable of simulating or imitating a real or imaginary world and generating artificial sensory stimulation. In the literature, fully immersive VR has many advantages for learning acquisition (Makransky et al., 2019). It is currently used in various fields and applications: medicine and therapy (Bisso et al., 2020; Ferreira & Menezes, 2020; Qu et al., 2022), education (Hein et al., 2021; Rosendahl & Wagner, 2023), skills development (Bizami et al., 2023; Coban et al., 2022; Corrigan et al., 2023; de Paula Ferreira et al., 2022; Mesa-Gresa et al., 2018). The interest in social skills and social communication impairments in autistic people is not surprising, as they should be an important target in educational interventions since these abilities are important in promoting adaptation and social participation (Wolstencroft et al., 2018). Exploring these skills through VR in a recreational context has been limited to date. However, this technology offers an immersive experience that can be particularly beneficial for autistic children. By combining the fully immersive nature of VR with bespoke activities, we are providing opportunities for autistic people to learn, grow and participate socially with their peers. This immersive technology opens up new possibilities for inclusive leisure activities in the community that can be enjoyed and appreciated by all.

VR can be non-immersive (via computer screens), semi-immersive (via large screens such as televisions) and fully immersive (Rose et al., 2018). There are three main types of fully immersive VR technology: VR headsets or head-mounted displays (HMDs), on-board simulation systems and CAVE systems. These systems cut the user off from reality in a totally artificial environment. The HMD is the most immersive technological tool, but also the most complex. An image is generated for each eye by software which, depending on head movements, has an impact on content and viewing angles. The brain combines these two images to create a 3D vision. To provide the deep sensation of experiencing the scene and avoid inconveniences such as motion sickness, the software must generate images fluidly and in real time. When designing the virtual environment, this speed means finding a compromise between performance and visual rendering.

According to the authors, not all autistic people can use HMDs due to the increased variability of sensory sensitivity or the discomfort associated with different stimuli in the virtual environment. Indeed, this discomfort in autistic people is mainly related to the total immersion of participants, who are more sensitive to cyber discomfort than neurotypicals (Newbutt et al., 2016) in particular due to their vestibular system. Secondly, integrated simulation systems are simulation spaces where the participant experiences total immersion, interacting with real equipment in environments that simulate real-life situations (Kapinski et al., 2016). The system is useful for professional training and specific functions (Kapinski et al., 2016; Muhanna, 2015). However, this specific equipment is expensive and requires a large location (Muhanna, 2015).

Finally, the original CAVE system (Cruz-Neira et al., 1992) has a pseudo-tridimensional structure in which the virtual environment is projected onto several two-dimensional screens placed around the user (Dechsling et al., 2022). This system is generally linked to a 10' by 10' by 10' cube (Cruz-Neira et al., 1992, 1993) whose faces serve as projection screens. The projection is designed to merge the cube with a sphere, creating an effect of depth (Cruz-Neira et al., 1992; Muhanna, 2015). Interaction between the user and the environment is achieved by analysing real-time images from motion sensor cameras. It does not require any portable accessory (Dechsling et al., 2022) and the CAVE system can be used in a single or multi-user context (Manjrekar et al., 2014; Mayer et al., 2023). In the literature, CAVE technology is considered expensive, as are non-HMD technologies (Guilbaud et al., 2021) and to compensate for this, several systems derived from CAVE technology have emerged. ".

With the aim of developing new inclusive and immersive leisure activities, the CAVE system appears to be an ideal technological candidate to address the challenges of social participation for autistic people. This study aims to review the state of knowledge on how CAVE technology can help autistic people enhance their social participation in the community. To date, recent studies have mainly identified therapeutic uses, without focusing on the use of the technology for recreational purposes. To address this gap in the literature, this study aims to answer the following questions: .

1. What is the current state of the art of CAVE technology, its context of utilization, and its benefits?
2. Can CAVE technologies enable the development of social skills, and if so, how?
3. What characteristics of CAVE technology act as barriers or facilitators to the social participation of autistic people?

To assist in the analysis of CAVE technologies, prior to addressing our research questions, we propose a classification based on three components that will define the CAVE system, in Section 2. The remainder of the study is organized as follows: Section 3 describes our methodology. Section 4 presents our results. Section 5 discusses the results. Section 6 proposes recommendations for future research. Finally, Section 7 presents our conclusions.

2. Background

Different types of CAVE are reported in the literature (Muhanna, 2015). However, there is no common taxonomy or typology to classify those systems. In line with that, this section introduces a CAVE classification framework to help us answer the research

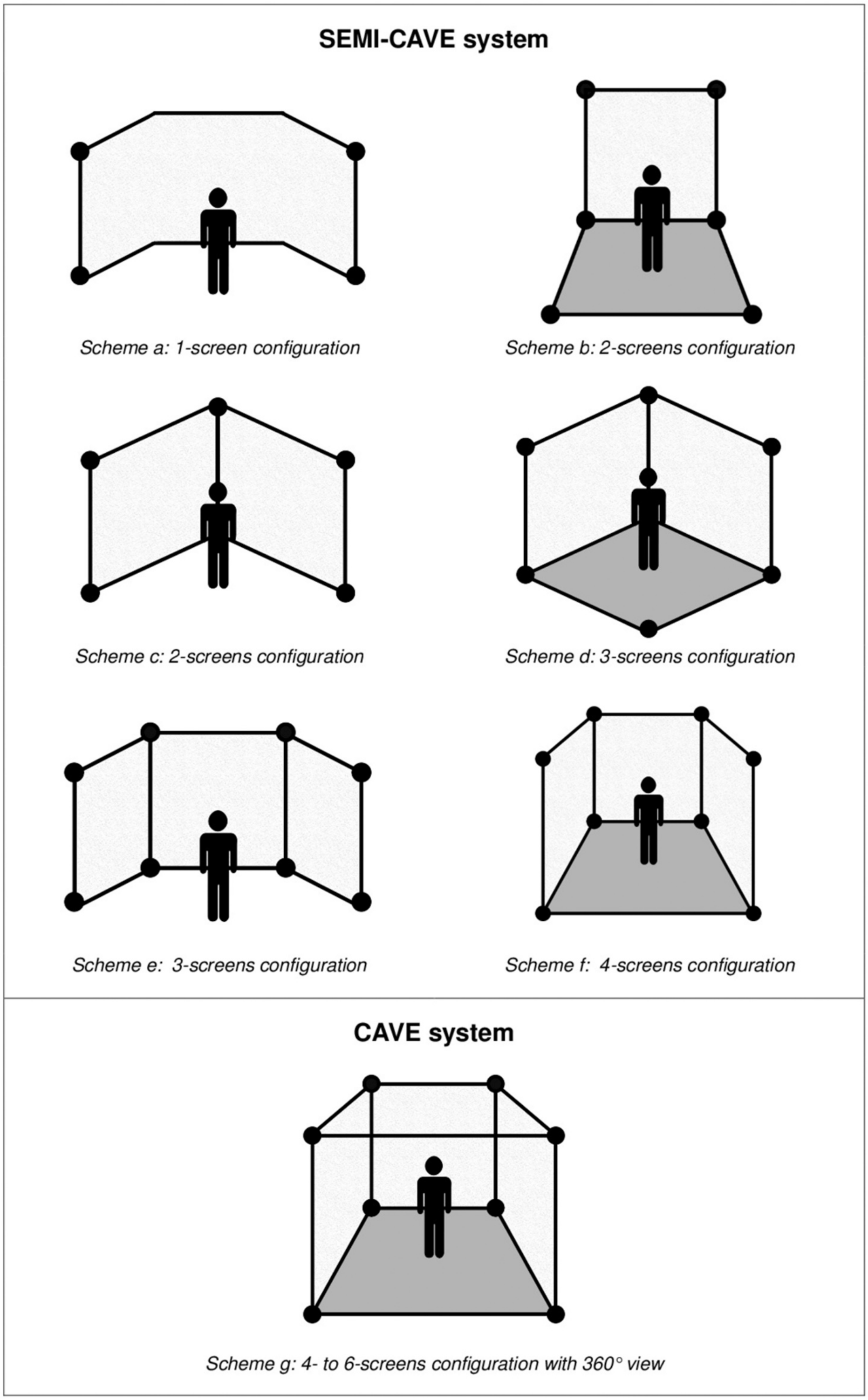

Fig. 1. CAVE classification framework.

questions in the introduction properly. It focuses on the three components that define the CAVE system: (1) number of screens used (Fig. 1); (2) type of immersive virtual environment (IVE) projection and (3) interactivity devices.

In the literature, the words “sides”, “walls” and “screens” are used to describe the delimitation of the CAVE system and its projection surface. In this article, we prefer the term “screen” as it better describes the nature of this component, particularly in view of the new indirect projection methods. The number of screens is the first component defining the CAVE or SEMI-CAVE. The CAVE has 4 to 6 screens and a viewing angle of 360 degrees. In this article we designate as SEMI-CAVE a 1- to 4-screen configuration and a viewing angle of less than 360 degrees. Therefore, there are 7 types of configurations, one CAVE (diagram g, Fig. 1) and six SEMI-CAVEs (diagrams a to f, Fig. 1). A first configuration proposes 1, 2 or 3 vertical screens with a view of 180 to 320 degrees (diagrams a, c, e, Fig. 1). The participant is positioned on a horizontal plane facing vertical screens, while the IVE is projected onto these vertical planes only. The next configuration is a viewing angle of less than 180 degrees from 2 screens (diagram b, Fig. 1). This configuration consists of one vertical screen and one horizontal screen. The participant is positioned on the horizontal plane and faces the vertical plane, while the IVE is projected onto both planes. Another configuration consists of 2 vertical screens and 1 horizontal screen with a view of 180 to 320 degrees (diagram d, Fig. 1). The participant is positioned on a horizontal screen facing vertical screens, while the IVE is projected onto these vertical planes and the floor screen. Finally, the system can be configured with 4 screens as shown in diagram f of Fig. 1, with a view of up to 320 degrees. This configuration consists of three consecutive vertical screens, with a horizontal plane used as the fourth screen. The participant is positioned on the horizontal plane, facing the three vertical planes, while the IVE is projected onto the three planes and the horizontal plane. This configuration consists of an immersive cube in which the IVE is projected onto the four vertical faces of the cube, and/or onto the lower horizontal face and/or the upper horizontal face, giving a 360-degree immersion without dropout. In this configuration, the participants is positioned on the lower horizontal face, and it is assumed that the level of immersion is greater in this configuration than in the previous ones.

The second component is the CAVE system IVE projection mode. There are two possible modes of projection: direct (Fig. 2a) or indirect (Fig. 2b). Direct projection involves using a video-projection system to project the IVE directly onto a screen from within the system. Indirect projection involves projecting the IVE from outside the CAVE system onto a mirror oriented to reflect the image vertically. This method of indirect projection uses a larger footprint than direct projection, since it requires the installation of devices all around the CAVE system.

The third component is the type of interactivity that can be experienced with the IVE. According to Motejlek and Alpay (2021), to be interactive, the system must recognize the signals sent by the user. The author defines 4 categories of user interactivity: user tracking, general-purpose controller, special controller, and no interaction. User tracking is a system that scans the user’s position via the body, eyes, hands, or the whole body. General controllers are receivers of movement information from the user and transmit this data to the application. A special controller is an input controller that cannot be reproduced by a general controller or by user tracking as, for example, tools used in medical training. No interaction means that the application is not interactive with the user. To take into account the specific nature of the CAVE system, we have added 2 categories of interactive objects to these 4 categories: sensory hardware and smart objects. The sensory hardware consists of intelligent devices that provide sensory stimuli as in a Snoezelen room (Lancioni et al., 2002) and are activated during the simulation with user interactivity (Garzotto & Gelsomini, 2018). The intelligent objects are connected to all the components of the CAVE system and allow to modify the simulation in just a few steps (Garzotto & Gelsomini, 2018).

3. Methodology

3.1. *The systematic review strategy*

Systematic research was conducted using the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA 2020) protocol to evaluate the effects of social and educational interventions (Lorenzo et al., 2023; Page et al., 2021) through immersive CAVE technology or a technological equivalent meeting our classification criteria. Our research targeted participants diagnosed with ASD without age exclusion. The development of inclusive and immersive leisure activities aims to induce the social participation of young autistic people and their families, both parents and siblings. Within this framework, it seemed obvious to include studies in

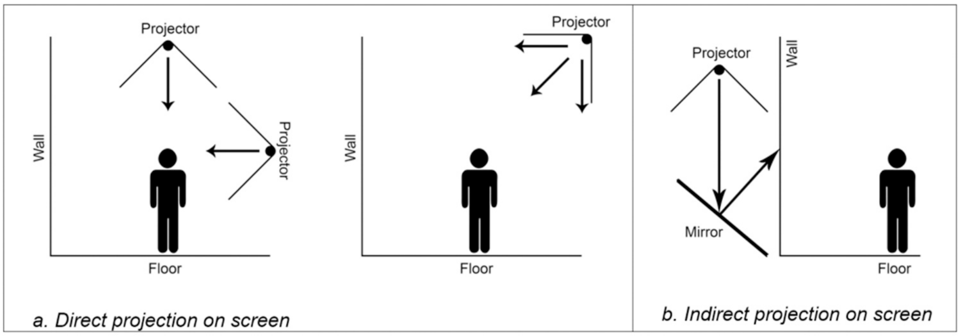

Fig. 2. Projection mode class.

which the participants were children as well as adults. Indeed, in the interest of inclusion, it is relevant to think of these activities as being for everyone, and therefore to examine the effects of CAVE-type technologies on adults as well as children. Interventions had to involve the CAVE immersive system or an equivalent technological system such as the "blue room" or "magic room".

3.2. Data collection

Seven databases were consulted for the analysis: American Psychological Association PsycINFO (APA PsycINFO), Education Resources Information Center (ERIC), ProQuest Advanced Technologies and Aerospace, ProQuest Dissertations and Theses Global, PubMed, Scopus, and Web of Science. The consultation took place on December 18, 2022. The following search terms were used: "autis* " and "CAVE" OR "immersive cube", "simulation cube", "immersive dome", "immersive box", "immersive room", "blue room" and "magic room". The following terms were not used: "ASD" when associated with the term "CAVE" but related to marine biology, or "virtual reality", which refers to various non-CAVE technologies. Other inclusion criteria were set: publications in English only, peer-reviewed publications, and publications between 1992 and 2022.

The research described above was carried out independently by two authors. None filters like specific research categories or domains were used. Instead, our search strategy was broad, aiming to capture a comprehensive range of studies relevant to our research objectives. This approach ensures that our review is inclusive and reflects the interdisciplinary nature of the research on CAVE

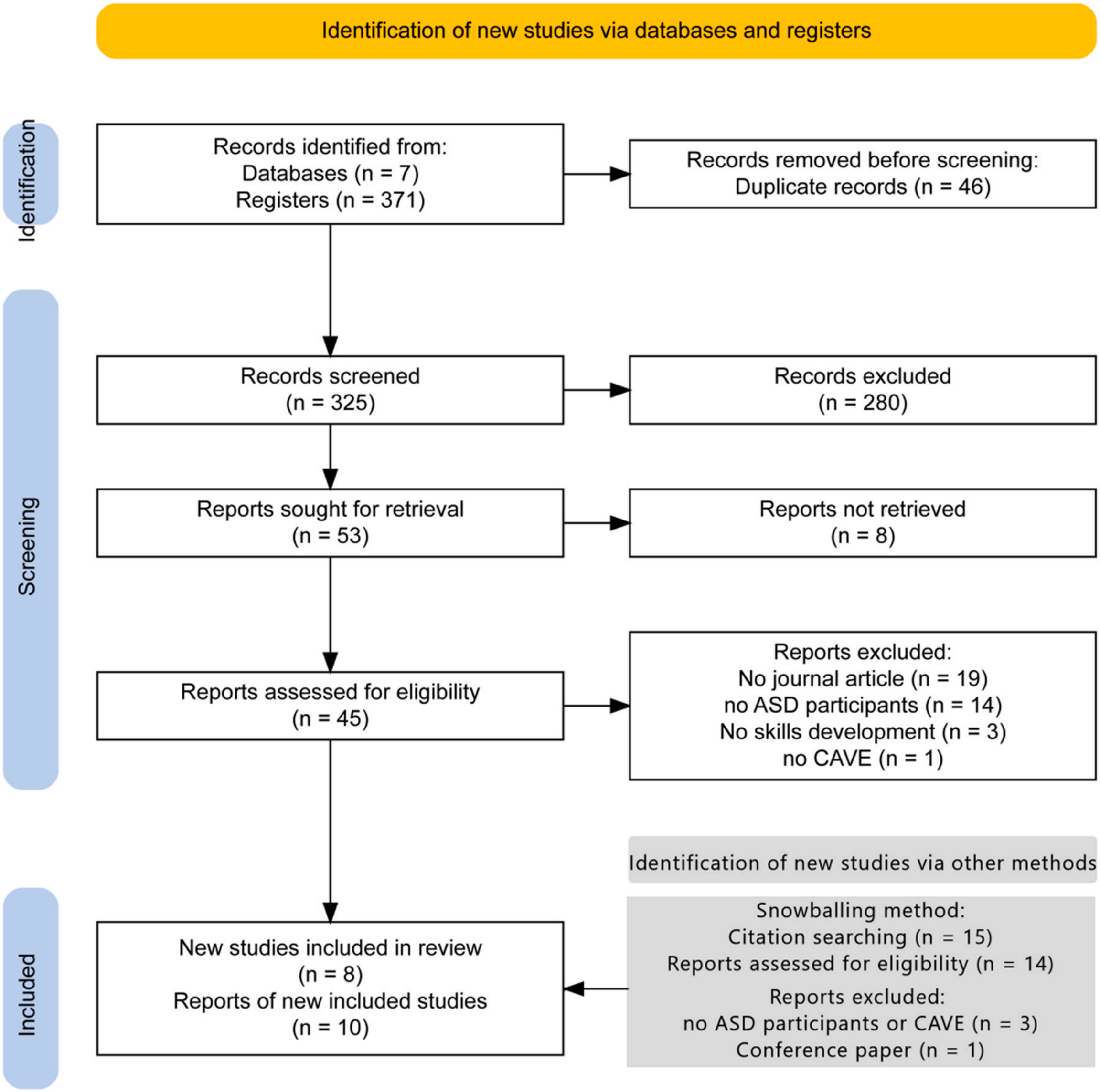

Fig. 3. Prisma 2020 flow diagram producted with the PRISMA Flow Diagram tool (Haddaway et al., 2022).

technology and its applications. The results were compiled, duplicates were removed and the articles were analyzed separately, according to a triangulation by investigators (Bengtsson, 2016). The authors then compared their results: articles in disagreement were discussed and, in the absence of unanimity, submitted to the third author, who decided whether to retain or withdraw the article from the study. The bibliographic references of reviews, meta-analyses, and new articles were analyzed to apply the snowball method (Wohlin, 2014; de Paula Ferreira et al., 2021). References that used a CAVE system with autistic participants and that we had not already retained were added to our analysis. Finally, four exclusion criteria were chosen: articles in languages other than English; articles published in a form other than peer-reviewed; articles that did not deal with the CAVE system; and articles that used CAVE technology in populations other than autistic people. After analysis, 18 articles published between 2010 and 2021 were selected, predominantly originating from the research domains of life sciences biomedicine, science technology, and social sciences (see Fig. 3). The search protocol is summarised in Table 1.

3.3. *Data analysis*

Data were extracted and coded according to the following categories: (1) Participants characteristics including gender, age, specific diagnosis, cognitive profiles; (2) CAVE technology characteristics according to the typology presented; (3) Social skills and social participation interventions; (4) Mono- or multi-participant VR experience; (5) Definition of social skills; (6) VR CAVE development purpose and benefits; 7) CAVE application context; h) Intervention scenarios; (8) Duration; (9) Context of intervention; (10) Interactivity; (11) Co-participation; (12) Activity assistance; (13) Target skills domains; (14) Social skills outcomes; (15) Data collection methodology.

4. Results

The results section begins with a description of the study participants, followed by the corresponding outcomes for each research question. A qualitative and quantitative analysis of the studies included in the sample are summarised in Tables 2, 3 and 4. A total of 561 participants took part in studies involving a CAVE or semi-CAVE immersive room system. The majority of participants were autistic (n = 443; 79 %). However, in studies comparing ASD cohorts with TD cohorts, a total of 74 autistic individuals (39 %) were identified compared with 118 TD individuals (61 %). Six studies were conducted to compare the responses of autistic people to those of TD people. Among these studies, only Alcañiz Raya et al. (2020) had equal numbers of participants in both groups. The other studies had smaller sample sizes in the ASD group than in the control group, ranging from 3 to 16 in the ASD group compared with 7 to 34 in the TD control group, i.e. an average ratio of 1 autistic person for every 1.6 TD individuals (Elor et al., 2020; Garzotto & Gelsomini, 2018; Greffou et al., 2012; Halabi et al., 2017; Wallace et al., 2010). The autistic participants were aged between 4 and 60. Twelve studies (67 %) involved only children i.e. autistic people under 18 and three studies (17 %) involved only adults. Three other studies (17 %) involved children and adults. In the ASD cohort, a total of 321 males (72 %) and 55 females (12 %) participated in an experimental activity and 67 participants (15 %) were undefined (Butti et al., 2020; Halabi et al., 2017). All the studies (n = 18; 100 %) included in this review focus on autism. Four studies experimented activities with participants defined as “high functioning” (Lorenzo et al., 2013; Maskey et al., 2019b; Wallace et al., 2010) or without definition or IQ value (Halabi et al., 2017). In eight studies (44 %), autistic people were found to have co-occurring conditions. Participants with developmental disorders (DD) (n = 8; 44 %) and other disabilities (OD) (n = 8; 44 %) were included. However, in 50 % of the studies, participants were excluded due to co-occurring conditions associated with autism. The main reason given by the authors was their intention to address one condition only, meaning that autistic people were included only if they did not have other cognitive conditions, such as intellectual disability. Other authors (Butti et al., 2020) argued that they opted to exclude autistic people with challenging behaviours associated with their sensory needs. Ultimately, the authors concluded that the lack of adaptation in interventions or failure to consider the sensory needs of autistic people had hindered their participation in activities or experiments (Greffou et al., 2012; Maskey et al., 2014, 2019a, 2019b; Tsai et al., 2021; Valori et al., 2020). Parents of autistic children are rarely considered as active participants in VR activities with their children. Only one study involved parents as study participants (Maskey et al., 2019a). In other studies, parents are either involved as companions or serve roles in negotiating with the participant (Cai et al., 2013; Garzotto & Gelsomini, 2018), facilitating their participation or explaining the activity’s modalities to the participants.

Table 1
Search protocol.

Data source:	Scopus, Web of Science, PsycINFO, ERIC, ProQuest and PubMed
Search string:	“autis* ” AND (“CAVE” OR “immersive cube” OR “simulation cube” OR “immersive dome” OR “immersive box” OR “immersive room” OR “blue room” OR “magic room”)
Search fields:	Title, abstract and keywords
Period:	From 1992 to December, 18, 2022
Documents:	Articles
Language:	English
Domains:	All

Table 2
CAVE systemes configuration in new articles.

Publication	System	Configuration	Projection	Interactivity devices
Alcañiz Raya et al. (2020)	SEMI-CAVE	3 vertical screens (180˚ to 320˚)	Direct	User tracking
Butti et al. (2020)	SEMI-CAVE	1 vertical screen (180˚ to 320˚)	Direct	User tracking General propose controller
Cai et al. (2013)	SEMI-CAVE	1 vertical screen (180˚ to 320˚)	Direct	User tracking
Elor et al. (2020)	SEMI-CAVE	3 vertical screens and 1 horizontal screen (180˚ to 320˚)	Direct	User tracking General propose controller
Garzotto and Gelsomini (2018)	SEMI-CAVE	3 vertical screens and 1 horizontal screen (180˚ to 320˚)	Direct	User tracking Smart objects Sensory Material
Greffou et al. (2012)	SEMI-CAVE	3 vertical screens (180˚ to 320˚)	Indirect	User tracking
Halabi et al. (2017)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	User tracking
Ip et al. (2018)	SEMI-CAVE	3 vertical screens and 1 horizontal screen (180˚ to 320˚)	Indirect	User tracking
Jacques et al. (2018)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	User tracking General propose controller
Lorenzo et al. (2013)	SEMI-CAVE	1 vertical screen and 1 horizontal screen (< 180˚)	Direct	User tracking
Lorenzo et al. (2016)	SEMI-CAVE	1 vertical screen and 1 horizontal screen (< 180˚)	Direct	User tracking Smart objects
Maskey et al. (2014)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	General propose controller
Maskey et al. (2019b)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	General propose controller
Maskey et al. (2019a)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	General propose controller
Tsai et al. (2021)	SEMI-CAVE	3 vertical screens (180˚ to 320˚)	Indirect	User tracking
Valori et al. (2020)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	General propose controller No interaction
Wallace et al. (2010)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	User tracking No interaction
Yuan and Ip (2018)	CAVE	4 vertical screens and 1 to 2 horizontal screens (360˚)	Direct	User tracking

4.1. Uses and benefits of CAVE technology

To examine the state-of-the-art of CAVE technology, its context of use, and its benefits, we analyzed the technical aspects of immersive systems, including the viewing angle of the screen, projection method, and interactivity devices. While all the studies used a CAVE system, our classification revealed that the tested systems were not all similar. Indeed, the CAVE system was divided into two groups: CAVE (n = 8; 44 %) and SEMI-CAVE (n = 10; 56 %). According to the Fig. 1, four SEMI-CAVE configurations were identified in the studies: 1-screen configuration (n = 2; 11 %), 2-screen configuration (n = 2; 11 %), 3-screen configuration (n = 3; 17 %) and 4-screen configuration (n = 3; 17 %).

Moreover, our classification revealed that 15 systems (83 %) used direct projection of the IVE onto the screens. In this configuration, the authors indicated that the participants could see the projection equipment. Three systems (17 %) used an indirect projection system (Greffou et al., 2012; Ip et al., 2018; Tsai et al., 2021). This projection equipment was not directly available to the participants.

In terms of interactivity, several categories of interactivity can be used together in a CAVE system. The most frequent category of interactivity was the user tracking system in 14 studies (78 %). General-purpose controllers were used in 8 studies (44 %), intelligent objects in 2 studies (11 %) and sensory materials in 1 study (6 %). Special controllers were not used and, finally, no participation was observed in 2 studies (11 %) where the participants were simply viewers. Studies on CAVE technology can also be separated into mono- or multi-user activities. Mono-user activities, involving a single participant, were observed in 14 studies (78 %) and multi-user activities, where several users participated simultaneously, were identified in 4 studies (22 %). Moreover, CAVE technology was used in three contexts: community-based (n = 1; 6 %; Garzotto and Gelsomini, 2018), educational settings (n = 4; 22 %) and controlled research environment (n = 13; 72 %).

The objectives of autistic individual participation in the reviewed VR CAVE activities were to develop skills (n = 6; 46 %), observe autism-related phenomena (n = 6; 46 %), intervene for therapeutic purposes (n = 7; 53 %) or promote awareness (n = 2; 15 %; Cai et al., 2013, Ip et al., 2018). The studies highlighted a number of benefits for participants using CAVE technology. Various skills, such as social skills, were practised or even improved in 9 studies (Cai et al., 2013; Garzotto & Gelsomini, 2018; Halabi et al., 2017; Ip et al., 2018; Jacques et al., 2018; Lorenzo et al., 2013, 2016; Tsai et al., 2021; Yuan & Ip, 2018). Improving the quality of life of autistic people was mentioned in 8 studies, and 3 studies showed that this objective could be achieved by combating phobias, for example.

Finally, 3 studies noted that the use of a CAVE or SEMI-CAVE system could be brought back into the real educational environment and provoke a transformation of good practices to make them more inclusive: (Ip et al., 2018; Lorenzo et al., 2013, 2016). Other studies report that the activities of a CAVE system can help detect specific traits in autistic people (Greffou et al., 2012 or be used in the diagnosis of ASD (Alcañiz Raya et al., 2020). Finally, other studies have shown that autistic people are receptive to CAVE's IVE and IVR systems (Valori et al., 2020; Wallace et al., 2010).

To further understand the expected or potential benefits of CAVE technology, we examined the motivations of researchers studying this field. Subsequently we examined the objectives of the various identified studies, grouping them according to Chong's taxonomy

Table 3
Summary of the studies.

Publication	Participants	Age	Diagnosis	Tech	User	Benefits
Alcañiz Raya et al. (2020)	N = 49; n(A) = 21 M/3 F; n(TD) = 16 M/9 F	4-7	ASD	SEMI-CAVE	MONO	contribution in diagnosis: observe head movements of participants to discriminate ASD and TD
Butti et al. (2020)	N = 42; n(VR-spirit) = 21; n(control) = 21	7-25	ASD, DD	SEMI-CAVE	MONO	increase quality of life: neurohabilitation in some abilities
Cai et al. (2013)	N = 15; n(A) = 2 F/13 M	6-17	ASD, OD	SEMI-CAVE	MONO	develop communication skills; helping ASD children; protecting endangered species
Elor et al. (2020)	N = 40; n(A) = 3 F/10 M; n(TD) = 15 F/12 M	19-30	ASD, OD, DD	SEMI-CAVE	MULTI	advantageous for collaborative task-based needs; observe emotionally receptive to iVR Exercise
Garzotto and Gelsomini (2018)	N = 19; n(A) = 1 F/7 M	8-13	ASD, OD, DD	SEMI-CAVE	MONO	practice social, emotional, cognitive and motor skills; learning effects faster than traditional school interventions; helping them to exercise the perceptual system
Greffou et al. (2012)	N = 50; n(A) = 3 F/13 M; n(TD) = 34	12-33	ASD	SEMI-CAVE	MONO	observe the postural hypo-reactivity from visual environment and development to discriminate ASD and TD
Halabi et al. (2017)	N = 10; n(A) = 3; n (TD) = 7	4-12	HFA	CAVE	MONO	develop social skills; increase quality of life
Ip et al. (2018)	N = 94; n = 86 M/8 F	7-11	ASD	SEMI-CAVE	MULTI	develop social skills; increase quality of life; promote and experiment inclusive education
Jacques et al. (2018)	N = 3 M	NA	ASD	CAVE	MONO	develop social skills in autistic adult; observe the skills improvement process
Lorenzo et al. (2013)	N = 20; n = 16 M/4 F	8-15	HFA	SEMI-CAVE	MONO	develop executive functions and social skills; transfer the knowledge in a real classroom; continue learning; support the educational intervention
Lorenzo et al. (2016)	N = 40; n(A) = 29 M/11 F	7-12	ASD, OD, DD	SEMI-CAVE	MONO	develop emotional behaviours in a real school environment
Maskey et al. (2014)	N = 9 M	7-13	ASD, OD, DD	CAVE	MULTI	overcome the phobia: tackle their target situation in real life
Maskey et al. (2019b)	N = 8; n = 4 M/4 F	18-60	ASD, HFA, OD, DD	CAVE	MULTI	observe the techniques practised by the participant to help parents support them; increase quality of life; readaptation with no impact from phobia
Maskey et al. (2019a)	N = 32; n = 25 M/7 F	8-14	ASD, OD, DD	CAVE	MULTI	increase quality of life with phobia
Tsai et al. (2021)	N = 3 M	7-9	ASD	SEMI-CAVE	MONO	develop social skills and motivation to learn and generate empathy; maintain their focus and better recognize affective expressions
Valori et al. (2020)	N = 9; n = 4 M(c)/5 M (ad)	8-39	ASD, OD, DD	CAVE	MONO	increase quality of life
Wallace et al. (2010)	N = 10; n(A) = 1 F/9 M, N(TD) = 2 F/12 M	12-16	ASD, HFA	CAVE	MONO	know the sensory effects of the imersive environment in CAVE on autistic children
Yuan and Ip (2018)	N = 94; n = 64 M/8 F	7-10	ASD	CAVE	MONO	develop different skills

Coding - Participant samples: ad = adult, c = children, F = female, M = male, N = total sample, n = sub-sample, A = autistic participant TD = typical development participant - Diagnosis: ASD = autistm spectrum disorder, HFA= high functionning autism, OD = other disorder (ADHD, language disorder,…), DD = developpemental disorder (Down syndrom, cerebral palsy, etc).

(Chong et al., 2022). The category “Application” was the most frequent, describing researchers’ motivations for using CAVE systems. Researchers aim to make the CAVE system more accessible (n = 7; 39 %), improve participant performance (n = 8; 44 %), facilitate learning (n = 4; 22 %), and enhance user engagement and entertainment (n = 2; 11 %).

The second category, “Assessment Trends,” aims to assess the technology and its practices. This category is divided into two subcategories: “application of the technology or system” (n = 5; 28 %) and “usability and user experience” (n = 8; 44 %).

The third category, “Technology,” included research objectives to implement CAVE technology. This includes “Technology Promotion” (n = 6; 33 %), which describes the motivation of these researchers to promote the use of the technology and boost technology acceptance, “knowledge transfer” (n = 1; 6 %) focusing on using VR technologies to ease the learning process, and “user experience promotion” (n = 1; 6 %) to enhance the quality of engagement and experience among VR users. The last category, “Design and Development Trends” includes motivations related to the design improvement and development of CAVE systems: “presentation process” (n = 3; 17 %), which aims to present a new medium method as a practical tool, “reconstruction and digitization” (n = 2; 11 %), which includes developing CAVE content that involves multiple images to construct 3D models from a set of images, and “system design” (n = 1; 6 %), which focuses on aiding the development and presentation of the methodology. These findings highlight the diverse research objectives, emphasizing the multifaceted nature of VR technology implementation and evaluation.

4.2. Using CAVE to development social skills

Among the 18 studies using VR CAVE technology, only 8 (44 %) focused specifically on the development of social skills (Table 4).

Table 4
Intervention in social interaction.

Article	Intervention	Population, context of intervention and interactivity	Co-participation and activity assistance	Target skills domains	Outcomes	Data collection
Garzotto and Gelsomini (2018)	Free play scenario Group activities with virtual stimulation projections and intelligent objects. Long term intervention 3 months; weekly sessions 6 sessions; 35 min average	Children School setting Cyber-personal	Group experience Assistance during IVR (2 adults)	Multiple Prerequisites to communication Interaction Emotional Executive functioning Motor	Positive user experience Skills improvement All social developmental skills demonstrated improvements: Communication increased 64 %; improvement in verbal skills and intentional communication. Relational area Increased 28 % Emotion area increase from 25 % up to 80 %	Researcher made observation form follow up diary Interviews
Halabi et al. (2017)	Role play “greeting” scenario; 3 conditions: (1) desktop computer, (2) Oculus Rift HMD,(3) CAVE immersive display 2 sessions; 20 min	Children Controlled research environment Resolution of social situation	Single participant Embedded assistance	Multiple Interaction	Positive user experience Skills Developed CAVE had higher general impact and obtained the desired response in less time. Immersion, satisfaction TD evaluated CAVE and HMD higher than ASD and ASD evaluated desktop higher than TD.	Researcher made Questionnaire: usability satisfaction and immersion level. Machine measure Time response
Ip et al. (2018), Yuan and Ip (2018)	Simulation of social situations 6 scenarios in 3-steps interventions 14 weeks, 2 sessions week. 40 min session in 3 steps	Children Controlled research environment Participatory, Resolution social situation and Cyber-personal	Single and group participants Assistance Pre-IVR During and Embedded IVR	Multiple Interaction Emotional Executive functioning	Skills Developed Significant improvement in emotion expression, regulation, and social interaction. Teachers reported improvements but results do not show improvements on emotion recognition. Control group improved significantly more than the training group on adaptive skills.	Standardised Raven’s Progressive Matrices Childhood Autism Spectrum Test Face Tests with adaptations and Eyes Psychoeducational Profile, (PEP-3) Behaviours Assessment System, 2nd Edition Researcher made: Parents Log Book
Jacques et al. (2018)	Simulation of social situations 5 virtual scenarios: (2) social interactions decoding (3) social cognition training Number of sessions and duration not specified.	Adults Controlled research environment Participatory	Single participant Assistance during IVR	Multiple Emotion recognition Social awareness Executive functioning	Skills Developed Overall improvement in participants’ ability to detect social cues; propose alternative behaviours and evaluate consequences of their actions. Participants (2/3) self-reported a reduction in maladaptive Behaviour Parents reported improvement in social decoding for all participants and in social skills for 2/3.	Standardised Social Interaction and Self Statement; social cues (CPS); social skills (CPI) Researcher Made Personal notes in a logbook questionnaire
Lorenzo et al. (2013)	Role Play 16 primary and 16 secondary social school’s scenarios. Each student	Children and adolescents Controlled research environment	Single participants Embedded Assistance in	Multiple Interaction Executive functioning Emotion	Skills Developed Generalization of application Students improved the acquisition of	Researcher made Observation grid Interviews with students and tutoring teachers Machine measure

(continued on next page)

Table 4 (*continued*)

Article	Intervention	Population, context of intervention and interactivity	Co-participation and activity assistance	Target skills domains	Outcomes	Data collection
	completed the 16 scenarios 5 times = 80 sessions. 25 min each, 2 times week	Resolution of social situation	IVR and Post IVR assistance		executive functions and social skills. The lack of structure and understanding of the task can induce difficulties. Acceptable transfer into the classroom	Automatic detection system
Lorenzo et al. (2016)	Role Play 10 social virtual scenarios in two conditions (1) IVR and (2) VR. 10 months; 4 different sessions each month; 35 min sessions	Children Controlled research environment Resolution of social situation	Single participants Assistance Pre-IVR; During IVR and embedded in the IVR	Multiple Emotion Interaction	Skills Developed Generalization of application IVRS is a useful tool in the acquisition and development of emotional competences in students with ASD. In the IVR condition students express significantly more appropriate emotional behaviours than desktop in VR. The emotional behaviours improved in real school	Researcher Made Self-reported Interviews observation grids Machine measure Automatic detection system
Tsai et al. (2021)	Role play 36 possible social situations. 2 conditions: (1) 3D virtual role play; (2) real-time self-role-play animations with their virtual counterpart. 8-10 weeks; 30-40 min	Children Controlled research environment Resolution of social situation	Single Assistance Pre-IVR; During IVR and Post IVR	Multiple Emotion recognition Social interaction Social awareness Executive functioning	Skills Developed Positive user experience Maintenance measures Moderate changes in the ability of the three children to recognize and understand facial expressions and body language of the real and virtual; The experience of social learning reported as interesting and enjoyable. Children enjoyed seeing themselves in action The learned behaviour's maintained over time	Standardised Vineland Adaptive Behaviour Scales Social story tests Scoring quality of role-playing game Researcher made Interviews and self-reported Machine measure Record of body movement
Wallace et al. (2010)	Simulation of social situations 3 scenarios 1 session; 3 scenarios presented in a fixed order	Children and adolescents Controlled research environment Passive	Single participant	Multiple Interaction	Autistic Children responded as typical children. Level of engagement was also similar for the two groups No sensory issues, nausea or dizziness. Autistic Children experienced the same social difficulties in the IVE scenario as in the real World.	Standardised measures Sense of Presence Inventory (ITC-SOPI) Social Attractiveness Questionnaire

Although the proposed scenarios varied greatly, they can be grouped into three main categories inspired by Duncan et al. (2012). Role-play was the most frequent intervention (n = 4; 50 %). In these scenarios, participants were required to interact with an avatar or demonstrate expected social behaviours. Simulation of social situations where the participant experiences a social activity without interacting with avatars was the second most frequent activity (n = 3; 38 %). Free-game play was used in one study (12 %). Duncan et al. (2012) typology did not include the simulation of social situations.

The duration of interventions also varied greatly, ranging from a single session of a few seconds to multiple sessions per week over several months. With the exception of Lorenzo and his team (Lorenzo et al., 2013, 2016) who conducted their interventions in 40-week periods, the majority of interventions lasted between 10 and 14 weeks. The most common weekly frequency was one session per week (n = 3; 38 %), while two interventions (25 %) were conducted every fortnight. In other studies, the interventions were conducted in a single session (Wallace et al., 2010) or the researchers did not specify the number of sessions per week (Halabi et al., 2017; Jacques et al., 2018). The average session time was 22 min. Most interventions (n = 6; 75 %) were conducted with school-age children. Two studies also focused on the adolescent population (Lorenzo et al., 2013; Wallace et al., 2010) and one on the adult population (Jacques et al., 2018).

The vast majority of studies took place in a researcher-controlled setting (7/8). Only one study took place in a school context (Garzotto & Gelsomini, 2018). The study by Lorenzo et al. (2013) is unique in that it took place in a laboratory, but the teachers in the school setting addressed the themes illustrated in the scenarios.

The most frequent level of interactivity (Ruscella & Obeid, 2021) was the resolution of a social situation (n = 5; 63 %). At this level of interactivity, users were presented with a task involving a social situation that they must respond to or resolve by interacting with the IVE. Other forms of interactivity (passive, participative, cyber-physical interaction) were equally present (n = 2; 13 %). Passive interactivity represents the lowest level of interactivity, since participants had no ability to interact with or influence the experience. In participative interactivity, participants could respond to questions related to their experience.

Finally, we propose the level of interactivity called “cyber-physical interaction,” which was not present in the original typology of Ruscella and Obeid (2021). During these activities, users had the opportunity to interact with the IVE through physical components, IT components, and intelligent objects. The studies of Ip et al. (2018), Tsai et al. (2021), Yuan and Ip (2018) proposed different scenarios with different levels of interactivity (participative, social situation resolution, cyber-personal, passive). The majority of activities (n = 6; 75 %) involved a single-person activity. Only Garzotto and Gelsomini (2018) proposed a group activity. Ip et al. (2018) and Yuan and Ip (2018) also included scenarios that could be conducted in a small group. These activities were designed to allow participants to adapt to the technology. Tsai et al. (2021) proposed several individual virtual scenarios in which two to three peers could observe the participant interacting with the avatar in the CAVE.

The level of support offered to participants varied between studies, with half the studies (n = 4) providing assistance at different moments. Assistance provided during the activity by the researcher or adult was the most common (n = 5; 63 %). Pre-IVR support and embedded support in the scenario were the two other most frequent types of support (n = 4; 50 %). Embedded support in the scenario could take the form of drop-down menus offering possible actions or an avatar suggesting/requiring an action from the participant. In the pre-IVR support, the experimenter could give some form of explanation or teaching concerning social rules or social skills. Post-intervention support (n = 2; 25 %) most often took the form of debriefing. All interventions targeted multiple social skills.

Interaction skills were the most targeted domain (88 %), including verbal and non-verbal information exchange, initiation interaction, reciprocity, and engagement in interaction. Emotional and executive skills were equally targeted (75 %). Emotional skills involved recognising and identifying the IVE avatar’s emotion and matching it to the correct designation (e.g., happy, sad, angry) or expressing the emotion in accordance with the context. Whereas executive skills involve the ability to focus on a task, make plans,

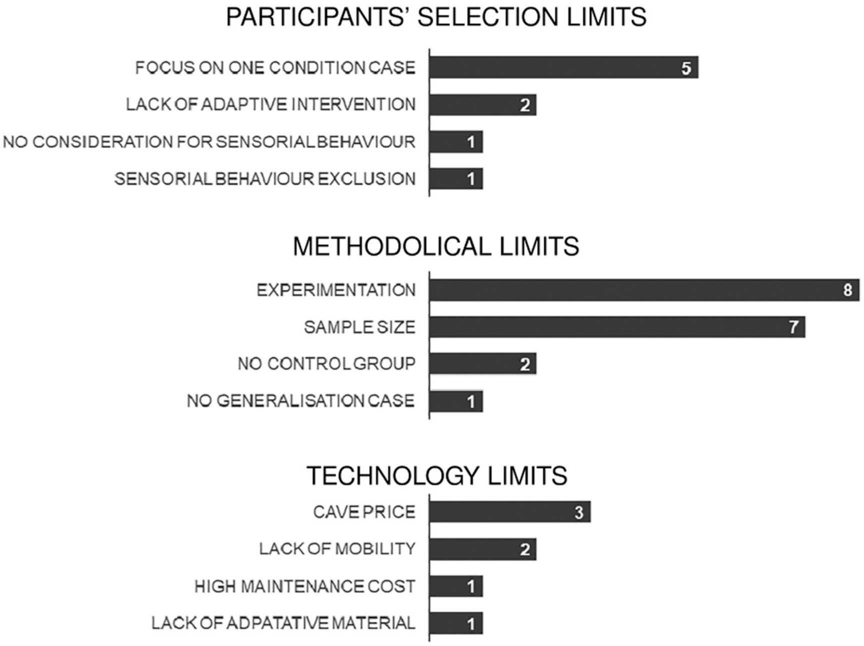

Fig. 4. Main challenges in the studies.

complete different tasks at once, or any combination of the three social awareness skills, which involve understanding causes of events or behaviours, respect for others and perspective taking were addressed in 2 studies (25 %) (Jacques et al., 2018; Tsai et al., 2021), while only one (13 %) study (Garzotto & Gelsomini, 2018) targeted the development of communication prerequisites. These included eye contact, listening to voice or sound, reacting to voice, sound, images, or physical objects, joint attention, etc.

The studies presented reported positive results regarding the development of social skills in 88 % of cases. Two studies (25 %) reported measurements in generalisation of results, while another study reported maintenance of acquired skills. Three studies (38 %) reported measurements of positive experience. The type of measurements reported varied greatly.

Tools developed by researchers were more common (75 %) compared to 50 % of studies that reported standardised tools. Half of the studies (n = 4; 50 %) used machine-based measurements. The most used measurement to determine improvement in social skills was self-reported (n = 7; 88 %) through questionnaires. Automated measurements and interviews were used in half the cases (n = 4), followed by direct observation (n = 3; 38 %) and direct testing (n = 1; 13 %). Automated measurements encompass time delay measurements, emotional expression recognition, and even body posture assessments.

4.3. CAVE adoption barriers and facilitators

The various studies reviewed uniformly highlight a range of constraints or limitations that counterbalance the benefits of CAVE technology utilization. These barriers are summarised in Fig. 4. The first barrier to the use of CAVE technology is the cost of purchasing and maintaining a CAVE system (Elor et al., 2020; Tsai et al., 2021; Yuan & Ip, 2018). In fact, the authors mention that use in schools or other organizations may be limited due to budget requirements for cost and maintenance. Two studies report a lack of mobility in the CAVE or SEMI-CAVE system (Elor et al., 2020; Tsai et al., 2021). In particular, they address the movement limits of participants in the CAVE. In addition, the size of the CAVE was considered to be a factor likely to limit interaction between participants.

The studies also revealed limitations in terms of participant selection and methodology. Knowledge of these study limitations is useful in providing input for future research. One of the main limitations cited in the selection of autistic participants is the selection of autistic participants with a single condition or without a particular condition (Greffou et al., 2012; Maskey et al., 2014, 2019a, 2019b; Tsai et al., 2021). Some authors also claim not to have taken into account the sensory needs of individuals (Butti et al., 2020; Maskey et al., 2019b; Valori et al., 2020). Other authors claim to have excluded participants because of their sensory needs (Butti et al., 2020). In all these studies, the authors seek to respond to the development of physical postures, to facilitate management of emotions such as phobias or to develop social skills.

A number of methodological limitations were also mentioned. In 8 studies, the authors cited experimental problems such as lack of data on participants' predisposition to video games (Ip et al., 2018; Wallace et al., 2010), problems in calibrating models to recognise movements or facial expressions of autistic participants (Cai et al., 2013; Tsai et al., 2021), need for long periods of adaptation to equipment such as 3D glasses (Lorenzo et al., 2013), management of confusion generated by the experimental system (Tsai et al., 2021; Valori et al., 2020) or passivity of participants who could not interact with the IVR (Wallace et al., 2010). Seven studies reported sample size limitations (Alcañiz Raya et al., 2020; Cai et al., 2013; Garzotto & Gelsomini, 2018; Halabi et al., 2017; Jacques et al., 2018; Maskey et al., 2019b; Tsai et al., 2021). In these studies, the number of autistic participants ranged from 3 to 24. Two studies criticised the lack of a control group (Garzotto & Gelsomini, 2018; Maskey et al., 2014) and a final study explained that it had not generalised the interventions outside the CAVE (Jacques et al., 2018).

As well as listing these limitations in their studies, the authors give a number of noteworthy suggestions to facilitate participant involvement. The majority of the articles report the positive effect of having an adult support the participant, whether they be a parent, educator, teacher, therapist or simply a peer (Cai et al., 2013; Garzotto & Gelsomini, 2018; Ip et al., 2018; Maskey et al., 2014, 2019b; Yuan & Ip, 2018). The support person has a well-defined role which helps to reassure and positively stimulate the participant (Maskey et al., 2019b). One study reports that taking into account the various hypersensitivities of these participants was one of the factors that facilitated the participation of autistic people (Alcañiz Raya et al., 2020).

Finally, various technological and didactic elements were also used to facilitate participation. The CAVE system facilitates the participation of several people at the same time. This allows participants to interact both with each other and with the CAVE. Participants have a strong sense of presence, despite the lack of direct interaction. For non-verbal participants or those with limited cognitive abilities, passive interaction still allows them to observe the CAVE. Furthermore, the advantage of this system is that it makes good use of literacy and visual information, which helps to structure the information and bring relevant information to the participant (Maskey et al., 2019a). These points are supported by the use of avatars who communicate in English, for example (Halabi et al., 2017).

5. Discussion

The literature review identified 18 articles on the use of "CAVE" technology in various application contexts for autistic people. This review, which focuses exclusively on this technology, provides new elements and thus complements the various reviews previously carried out on immersive or VR technologies (Dechsling et al., 2022; Dechsling & Nordahl-Hansen, 2023; Mesa-Gresa et al., 2018; Mosher et al., 2022). Analysing participant data revealed an imbalance between the number of autistic and allistic individuals, with an average ratio (ASD:TD) of 1:1.6, ranging up to 1:2.3 (Halabi et al., 2017). This bias was justified as acceptable since the smaller number of autistic individuals would be an equivalent group to the larger number of allistic participants (Halabi et al., 2017; Happé, 1995). However, this assumption suggests that the responses of autistic individuals are less diverse than those of allistic individuals. Yet ASD is defined as a spectrum that reflects this high diversity in attitudes and responses to the environment. We therefore question the under-representation of autistic people in the comparative studies. In the autistic cohort, people with low ID are also under-represented or excluded from the studies. This bias reflects a well-known participant selection bias in social skills cited in the literature (Dechsling et al., 2022; Russell et al., 2019).

In addition, an unbalanced ratio between the number of autistic males and females was also noted, with a ratio (female:male) of 1:6. The under-representation of females in the studies also is well described in the literature (Dechsling et al., 2022). The recommendation is to focus more on recruiting female participants. However, in Canada, the male-to-female ratio reported in the literature is (Female:Male) 1:4 (Agence de la santé publique du Canada, 2018) although some authors believe that this ratio is underestimated (Loomes et al., 2017). We are concerned about the possibility of recruiting as many female as male participants, given the representation in the natural population.

5.1. What is the current state of the art of CAVE technology, its context of utilization, and its benefits?

CAVE technology has been used mainly in three contexts, with a preponderance in controlled research environments. Research in this experimental context aims to use CAVE technology to develop skills, recognise emotions, develop clinical applications, diagnostic and intervention, etc. These findings largely reflect those reported by Mesa-Gresa et al. (2018). Given the importance of skill development, particularly social skills in autistic people (Roche et al., 2021), it is understandable that a significant amount of research is focused on this area. However, we believe that these studies would benefit from being conducted in more naturalistic contexts. As reported by Dechsling et al. (2022), the novelty of the field may explain several limitations of the studies and challenges in applying these technologies in more natural settings. Nevertheless, we believe that using this technology in naturalistic contexts would have several advantages. Firstly, the participants' perspectives would be taken into account to a greater extent in the development of the technology, scenarios, and research objectives. Additionally, involving parents and peers in the activities would further enhance social relevance and generalisation of the findings (Parsons et al., 2020).

The use of CAVE and VR has benefits for autistic people, such as improving their quality of life or developing skills useful in everyday life. This is largely due to the active participation of autistic people. Indeed, by convention, autistic people, and especially children, seem to readily accept the use of immersive tools. These induce pleasure and great motivation (Dechsling & Nordahl-Hansen, 2023).

As a result, autistic people can be exposed to a wide range of possible scenarios, enabling them to practise or learn in educational or therapeutic contexts. For example, some authors put a great deal of effort in developing scenarios designed to develop emotion recognition (Lorenzo et al., 2016) or social skills (Lorenzo et al., 2013). These activities could be reinvested in the school context. These findings are supported by experimental approaches in the CAVE or SEMI-CAVE system.

Upon reviewing the studies collected, it became clear to us that the potential of CAVE technology is underutilised. None of the studies consulted were conducted in a leisure context. Additionally, only one study was conducted in a multi-user setting with social interaction between peers (Ip et al., 2018), and none of the studies explored the collaborative aspects of activity implementation. Only one study exploited the potential of the CAVE to stimulate or enhance interaction among users or between users and facilitators during the activity (Garzotto & Gelsomini, 2018). This can be attributed to the newness of the field (Dechsling & Nordahl-Hansen, 2023), the complexity of the technology (Muhanna, 2015), the associated costs (Elor et al., 2020; Yuan & Ip, 2018), and other factors (Tsai et al., 2021).

Leisure activities are defined as recreational moments during which people engage in enjoyable and unrestrained participation (Kelly, 2019). Many of the studies analysed in this context could be further explored within a leisure setting, specifically in a social leisure context. Social leisure activities involve families and communities in a beneficial social process for adults, parents and children alike (Kelly, 2019). These activities are recognised as important for the development of many skills as defined by (Mosher et al., 2022). They also afford the advantage of having greater ecological value and being multi-user. Our assessment reveals that activities using CAVE technology are primarily single-user experiences. In this regard, one could imagine that multi-user activities based on CAVE technology within the context of community leisure incorporate significant social interaction among the different participants: adults, adults and children, and children alone. This opens up greater opportunities for parent-child activities that have been largely overlooked until now.

Previously, parents were mainly used as resources for negotiation, to redirect activities, or simply as external observers, without actively participating alongside their children. Furthermore, therapists have been relied upon as cues in these activities, whereas this role could also be extended to the parents and the autistic person's entourage. Multi-user CAVE technology scenarios can also be used to propose inclusive activities that promote collaboration and interaction between autistic children and their non-autistic peers, as highlighted in (Parsons, 2015). In this context, CAVE activities can also raise awareness among the allistic peers by participating in shared interest activities, reducing the risk of stigmatisation. Consequently, the technology could be used as a leisure activity, and the CAVE system would be a good candidate for fostering interaction and social participation.

Moreover, Elor et al. (2020) emphasized a specific advantage of the CAVE system: collaborative actions. Simulations involving several users naturally encourage interaction between autistic individuals. This type of interaction enables autistic people to experience collaboration within a social leisure context and develop new social skills. Furthermore, single-user activities can be reinvented to accommodate several participants. The dolphinarium activity, for example, enabled participants to develop social skills for therapeutic purposes (Cai et al., 2013). This activity could be shared between parents and autistic children, or therapists and autistic people, to share a social experience while acquiring complementary skills. However, to be enjoyable for everyone involved, these leisure activities should be inclusive and, therefore, meet the needs of all participants.

Several studies using the CAVE system have identified a lack of appropriate intervention or ignorance of participants' sensory needs as a barrier to social participation for some autistics. The sensory system enables exploration of the environment, and the appropriate acquisition of skills essential to affective, cognitive and motor development (Garzotto & Gelsomini, 2018) included these elements of response to the participants' sensory needs. They showed that the range of stimuli, modes of interaction and play experiences with these objects helped to develop cognitive, emotional, relational, and communicative skills. However, the authors also noted that some sensory stimulation objects could overexcite certain young people. Immersive leisure activities that take into account the needs of autistic people in a CAVE system could therefore become inclusive leisure activities accessible to all, bringing the many benefits described here to both autistic and normally developing people.

Finally, the objectives related to technological research focused mainly on performance, a high level of acceptance of the technology, trends in technology evaluation and, finally, the promotion of the technology. This race to develop technology is important for technical and economic purposes. However, in the context of studies aimed at improving the daily lives of autistic people, supporting them in the development of skills or simply in the interest of social participation, it would be also beneficial for autistic people to develop inclusive scenarios and activities that would naturally lead them to develop skills, within the framework of social participation activities.

5.2. Can CAVE technologies enable the development of social skills, and if so, how?

Our research focused on the study of the immersive CAVE technology as a tool for developing social skills to facilitate social inclusion and enhance social participation. It is crucial to develop social skills in autistic individuals because they experience difficulties in developing these abilities spontaneously through socialization and may engage in behaviors that hinder social participation (McConnell, 2002). All the identified studies aimed at developing social skills reported positive outcomes in the acquisition of at least one of the targeted social skills. The emotional, interactional and executive domains of social skills showed the most progress. This highlights the significant potential of immersive CAVE technology to "teach" social skills.Moreover, studies comparing CAVE technology with other immersive technologies (Halabi et al., 2017; Lorenzo et al., 2016) reported a preference for CAVE technology among users and more positive results. Additionally, none of the studies reported signs of cybersickness, as described by Bradley and Newbutt (2018).

Despite these positive results, we add our voices to Mosher et al. (2022) and Dechsling et al. (2022) in advocating for future studies to better define the measured social skills and incorporate external outcome measurements that allow comparisons of study results and more in-depth analyses of the outcomes. This is not a new issue; Kavale and Forness (1996) previously indicated that authors demonstrate a preference for criterion-referenced measurements, but sometimes these measurements lack reliability or validity data to support their use. Norm-referenced measurements, which are more sensitive to the progress of individuals and allow better comparisons between studies, are seldom used.

Another aspect that we, researchers, should pay more attention to is the description of the conceptual framework and better explain the rationale between the measurements used and what we believe they measure. The use of immersive technologies and automatic detection systems makes it easier to gather data. However, it is crucial to ensure that what we are measuring supports our claims. For example, Halabi et al. (2017) reported that the response time of users in the CAVE condition is shorter for all users. While this result is interesting in itself, we may question whether it "verifies that the developed system is an effective tool for improving the communication skills of autistic children" (Halabi et al., 2017, p. 61). Upon reading the studies, we noticed that greater attention was paid to explain the methodological and technological aspects of the research than to conceptualising and explaining the theoretical foundations related to social skills. As Ke et al. (2022) indicates, this limits the explanatory scope of the results obtained and does not allow us to determine whether we are all referring to the same concepts.

In several studies we analysed, the targeted skills were not explicitly defined, and only broader domains were mentioned without being defined. Furthermore, the authors rarely assess the nature of the deficits in social skills and make little distinction between factors that may contribute to deficits, such as lack of knowledge, lack of practice or feedback, lack of cues or opportunities (Bellini & Heck, 2019; Gresham et al., 2001). The authors probably assume that the presence of social skills deficits is attributable to the nature of the autism condition. However, ASD is a heterogeneous condition and depending on the cause, different interventions or scenarios should be used (Howard & Gutworth, 2020). In this context, young individuals who lack knowledge could benefit from preparatory workshops that teach them social skills using best-suited practices, as suggested by Ke et al. (2022), Øzerk et al. (2021) and then expose them to social situations illustrating the situation or even their reactions to the situation, as demonstrated in Tsai et al. (2021) who provided in intervention support.

Similarly, young individuals who lack practice could benefit more from role-playing exercises that they could practise safely and as often as they wish. Those who lack cues or opportunities may benefit from greater support during scenarios, as shown in Lorenzo et al. (2016), or even the use of augmented reality inside the CAVE, as proposed by Mosher and Carreon (2021). This supports the use of programs tailored to the needs of users and multi-components Ke et al. (2022), Durlak et al. (2011).

In the studies reviewed, few authors used different types of VR scenarios (e.g., role-play and simulation of social situations) combined with other types of interventions. On the other hand, the vast majority of proposed interventions take place over an extended period, ranging from 10 to 40 weeks, with weekly or biweekly frequencies. This is relevant and highlights the importance of dosage interventions (Bellini & Heck, 2019). Social skills are complex and take time to master. In this sense, only three studies report measures of generalization (Lorenzo et al., 2013, 2016) and maintenance (Tsai et al., 2021).

Finally, we believe that one significant advantage of the CAVE with autistic individuals, in addition to those mentioned by the authors, is the ability to allow users to interact with the IVE while remaining connected to their environment and being able to interact with their peers, whether autistic or not. This unique quality of the CAVE was only used in 2 studies (Garzotto & Gelsomini, 2018; Ip et al., 2018). We believe that this unique property of the CAVE is underexplored and holds great potential for collaborative scenarios that promote greater social participation of autistic individuals, thus fostering inclusive activities.

5.3. What characteristics of CAVE technology act as barriers or facilitators to the social participation of autistic people?

The literature review identified three categories of limitations in the studies: technological limitations, experimental limitations, and exclusionary limitations. Firstly, the technological limitations are primarily linked to the high costs of purchasing, installing and maintaining the equipment. The limited popularity of CAVE systems is based on several factors, including their scale, size, complexities, and the need for expert operators. However, it is noteworthy that the technological landscape is evolving rapidly. As time progresses, the cost of technologies tends to decrease, making them more accessible. Even if portable CAVE systems (Cruz and Dirk) are now available at excepted prices of around $40,000, the acquisition for environments like schools or community centres remains a challenge. With technological advances and reductions in the cost of certain equipment, it is possible to envision a CAVE system that is less expensive, more adaptable and transportable. This approach could mitigate some of the current CAVE systems adoption limitations and enhance the feasibility of using it more widely. In addition, it would be relevant to compare the different configurations of CAVE and/or SEMI-CAVE systems in terms of immersion, sense of presence and widespread use. The cost of the different configurations has not been compared here but, logically, the simpler the structure of the CAVE system, the more the cost should be impacted. No data in the literature has compared the structures in terms of immersion and sense of presence, which could play a role in the participation of autistic people.

Secondly, experimental restrictions are connected to experimental biases. These biases are linked to the number of participants in the studies, or to the lack of a control group. This could be circumvented by proposing social participation activities with a CAVE system in both community and mixed school settings.

Looking specifically at the last type of limitation qualifying the exclusion of participants, these studies reveal a focus on particular conditions related to autism and often ignore, fail to accommodate or exclude other conditions such as sensory behaviours. However, addressing the sensory sensitivities of autistic people would facilitate learning, inducing motivation, self-regulation (Agostine et al., 2022) or participation (Bagatell et al., 2022; Clément et al., 2022). This participation is positive for the inclusion of autistic people with their peers, their families and adults in general. A United Nations (UN) report on the World Social Situation defines social inclusion as *"the process of improving participation in society, particularly for disadvantaged people, through enhancing opportunities, access to resources, voice and respect for rights"* (of Economic and Affairs, 2016). This means that our society is built on giving all children and adults the opportunity to be valued, respected and contributing participants. In the context of leisure activities, we add the notion of an inclusive leisure experience (Carbonneau et al., 2015). This involves the social participation of individuals in an activity that generates the development of each person's full potential, positive interactions between participants and adapted access to facilities. In our review, few studies are used in multi-user mode, i.e. with several participants interacting. However, some single- or multi-user activities, such as Elor et al. (2020), Garzotto and Gelsomini (2018) or Cai et al. (2013), could be reinvested with social participation in mind. By taking into account the sensory sensitivities of autistic people, we also meet the needs of other individuals, thus creating more inclusive activities to promote social participation among all, neurotypical and neurodiverse people.

6. Recommendations for future research

For future research, we recommend developing a new common taxonomy between CAVE technology and other immersive tools. In this article, we made a contribution to the terminology to be used when talking about CAVE technology and its uses. We have discussed the different types of CAVEs, technical aspects and user aspects, interactivity versus interaction. There are so many different configurations of CAVE technology, and so many different uses of it for different purposes, that we need to adjust and elaborate a clear nomenclature that can be used by all. This task is undeniably complex but crucial to ensure consistent conceptual references. In the absence of a consensus within the research community, it remains pertinent to complete a comprehensive common taxonomy for delineating the technical intricacies of CAVE technology and considerations related to users. For instance, we have noted that the terms "interactivity" and "interaction" are often used interchangeably. In the literature, interactivity is defined from a human-computer interaction perspective (Zhang et al., 2019), while interaction pertains to exchanges between people (VandenBos, 2015). However, in this SLR, the term "interaction" was frequently employed in the context of "interactivity," leading to confusion. This suggests that users develop social skills through interactivity with IVR. Still, in reality, social skills are nurtured and defined through interactions between individuals. Consequently, to foster the development of social skills in autistic individuals, this nuance implies the need to adapt CAVE activities and environments to encourage interpersonal interaction.

Furthermore, considering the cost variability associated with CAVE and its diverse configurations, it is imperative to compare different CAVE and SEMI-CAVE setups regarding their potential impact on skill development and social participation. Factors such as immersion level, viewing angles, and configuration space size should be taken into account. These configurations, each with its distinct cost implications, have yet to be comprehensively studied. It is worth acknowledging that the history of insufficient services for the autistic population and their families is well-documented (Malik-Soni et al., 2022). However, it is encouraging to note that technological evolution, characterized by decreasing costs and the diversification of interventions across various contexts, presents promising prospects for using these tools in stimulation centres, rehabilitation facilities, community centres, and schools. The absence of applied research in environments such as homes may constitute a significant gap, potentially associated with the size or cost of CAVE technology. Nevertheless, participatory research studies in community or school settings could support practices to develop social skills in leisure contexts.

We also recommend developing an autism-friendly CAVE concept that would also respond to the different sensitivities of autistic people and promote interaction and social participation. Indeed, the literature demonstrates the benefits of social participation, particularly for autistic people of all ages. Autistic people are naturally motivated in this immersion system, which is an asset in facilitating inclusion and social participation. This participation suggests that interaction between autistic people and their peers, as well as between adults (therapists, carers or parents) and autistic people, would be facilitated by this system. The benefits between autistic and/or allistic peers could enable the development of social skills as well as cognitive development. To achieve this, the scenarios should be in multi-player mode, and could be role-playing, social scenarios or collaborative games. The virtual environments should blend the developmental approach with leisure activities, so as to remain attractive and motivating models for autistic participants, while enabling them to take part in social situations.

In the literature, several authors have highlighted observations aimed at contributing to the development of virtual environments more in line with the preferences of autistic people (Finkelstein et al., 2013; Sampath et al., 2013). However, it is important to note that these observations are not always based on robust empirical data, underscoring the need for further exploration of design principles for the development of VR applications for autistic people (Bozgeyikli et al., 2017). An essential approach to better include the voices and perspectives of autistic people, especially when CAVE systems are utilized in experimental or research settings, would be to develop scenarios tailored for practicing social skills in a leisure context that is closer to their natural environment. This type of approach could provide a platform for gathering the preferences of autistic people regarding leisure activities and environments, thereby contributing to a more user-centered and inclusive design.

Moreover, we should continue our efforts to better define the skills we aim to develop and use standardized measures when they are available to complement measures built by researchers. Efforts should also be made to use measures of maintenance and generalization. These practices would allow us to better compare results across studies and assess if the effects extend beyond the experimental period. Autistic people of all ages could then find themselves included in attractive and inclusive leisure activities. Interactions between autistic people and adult parents or carers would create positive interactions that could be generalized to everyday activities. Adult-to-adult or family interactions with allist and autistic people would raise awareness of neurodiversity and autism, and create spaces for inclusion.

7. Conclusion

Our systematic literature review from 1992 to 2022 reveals that CAVE systems can enhance the social participation of autistic youth by helping develop their social skills and providing them with positive experiences in a virtual environment, as well as activities that leverage their strengths while minimizing cybersickness discomfort. This review also proposes a classification framework for CAVE systems, enabling comparison of existing systems.

Regarding our first research question, there is considerable variability in the configuration of CAVE systems. Our analysis identified a lack of consensus on the terms used to describe the components of the CAVE or the possibilities for interactivity and interaction with this system. This issue necessitates further analysis to clearly define these terms and establish a consensus within the scientific community. Although our study shows that autistic children demonstrate a preference for CAVE systems, not all CAVE systems are likely equally effective in supporting the engagement, participation, and learning of autistic children. Ongoing research is essential to refine and compare CAVE systems, particularly as these aspects are anticipated benefits observed by researchers. The context of use remains largely within controlled research environments. This limitation is not unique to CAVE systems, but it underscores the imperative to apply this technology in more natural settings.

Regarding our second research question, this study suggests that CAVE systems can support the development of social skills. This is primarily achieved through role-playing activities where the autistic youth interacts with the IVR in a single-participant format. However, one of the most significant advantages of the CAVE system is its ability to facilitate free interaction between participants and interactivity with the IVR. This opens up various intervention possibilities and scenarios where autistic youth can collaborate with peers to engage in various activities. From our perspective, it is also crucial to involve autistic individuals in developing scenarios that cater to their interests to better support their social abilities' development.

Regarding our third research question, our study identified several technological challenges related to cost and lack of mobility, which can hinder the widespread use of CAVE systems. Despite these obstacles, which future research has to address, we also identified unique qualities that merit further exploration. The CAVE system appears to have a lower sensory impact, and autistic youth seem to prefer this type of experience. Another notable advantage is its versatility since it can offer activities to autistic youth who require more support and have historically been offered fewer opportunities.

Our study reveals that this technology is underutilized and underscores the importance of developing a CAVE system that is both financially accessible and tailored to the needs of autistic youth. We believe that the CAVE system combines the benefits of virtual reality systems appreciated by autistic children while enabling multi-player activities where autistic youth can move beyond controllers to focus on the interactivity of the virtual environment and free interaction with other autistic or allistic youth, without being isolated by the use of goggles or other controllers. This may seem counter-intuitive or paradoxical, but the aim is to use the virtual environment of the CAVE system as a mediator to foster interactions between youth, or between youth and adults, that might not otherwise occur.

Although CAVE-based virtual reality is already available in a wide range of applications, we believe that its use in inclusive leisure contexts within community settings will enable autistic individuals to participate in virtual reality activities with their peers and generalize their interactions within the community. This can be achieved, among other ways, through the establishment of collaborations between academic institutions and community organizations, thereby promoting social innovation approaches. This will also promote more equitable access to technologies that they rarely encounter. These new approaches could not only improve the social interactions of autistic youth but also offer enriching educational and recreational opportunities, contributing to better social inclusion by bridging the gap between virtual reality and the real world.

Funding

This work was supported by Quebec’s Ministère de l’Economie, de l’Innovation et de l’Energie (MEIE) [N/Réf.: 2022–2026-PSOv2a-ETS-IS-63675].

CRediT authorship contribution statement

Isabelle Dabat Pivotto: Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **William de Paula Ferreira:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Vitor Matias:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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