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A survey on technological tools and systems for diagnosis and therapy of autism spectrum disorder

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ABSTRACT

Progress in Information and Communication Technologies (ICT) can make a real difference in the quality-of-life of persons with Autism Spectrum Disorder (ASD) by acting on several aspects, from customized software for communication, to emotion recognition, to social behavior and also to provide systems for the observation of the wide spectrum of manifestations, to ease the diagnosis, to support the therapy, and to monitor the improvement and the growth of children with ASD. This has been achieved by the introduction of a large number of innovative technologies, spanning from Internet of Things, to robotics, virtual and augmented reality, etc. Differently from other surveys on the same research area, we focus this survey on innovative technologies used in this field, and we organize a classification of the papers based on three different but strictly crossed axis, namely the triad of impairment (either communication, social interaction, or social behaviors), research purpose (either diagnosis or therapy), and system activity (either monitoring or intervention).

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1. Introduction

Autism Spectrum Disorder (ASD) is a neurodevelopmental disorder characterized by deficits in communication, social interaction, and repetitive restricted behaviors (American Psychiatric Association, 2013). It severely affects the way in which people interact with each other. Individuals with ASD experience the environment differently from a sensory point of view. (Narzisi et al., 2018) reported that the ASD prevalence for Italy is 18 per 1000, i.e., one in 55 children aged 7–9 years on rising trend. The situation in the United States is similar (Maenner et al., 2021). Currently, the only possible intervention builds on early diagnosis based on clinical observation (in Italy usually at 1.5–2 years of age), followed by intensive treatment. However, no matter how soon treatment starts, none of the current techniques can resolve ASD completely. People with ASD can acquire many abilities, become more autonomous, work, and even live alone. However, many autistic traits remain making quality-of-life severely compromised. In this perspective, it is clear that there is a constant need to complement early diagnosis of the syndromes as well as long-term therapies for individuals with ASD in their surrounding environment including family, school, hospital, coworkers etc.

In this respect, the use of technology has already made a difference in quality and efficiency of various services such as: i) ease ASD diagnosis (Dawson & Sapiro, 2019; Orlandi et al., 2012; Piccardi et al., 2021); ii) monitor improvement in children with ASD (Wall et al., 2012); iii) intervene in communication by massive production of customized software (Bosseler & Massaro, 2003; Coleman-

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Martin et al., 2005); iv) exercise emotion recognition (Bolte et al., 2002); and v) improve social behavior (de Arancibia et al., 2019; De Urturi et al., 2011). This has been achieved by introducing a wide spectrum of technologies, spanning from Internet of Things and wearable devices (Bondioli et al., 2019; Iakovidou et al., 2020), mobile and web applications (Almazaydeh et al., 2022; Narzisi et al., 2020), robotics (Huijnen et al., 2016; Ramírez-Duque et al., 2021), virtual and augmented reality (more recently even including metaverse) (Kojovic et al., 2021; Raya et al., 2020), just to mention a few.

This work aims to systematize this complex and fragmented scenario. We present a wide selection of the most relevant results in Information and Communication Technologies (ICT) within the scope of the ASD areas of intervention. Our work aims at a quick reference tool for researchers who need to better understand specific research papers, to enrich their general knowledge in the field or, as a reference point for future research. The review of the state of the art is based on the Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) methodology (Page et al., 2021). In contrast to other recent surveys (Abu-Amara et al., 2021; Alnajjar et al., 2020; Anagnostopoulou et al., 2020; Gallardo-Montes et al., 2022; Heath et al., 2021; Hosseinzadeh et al., 2021; Kohli et al., 2022a; Mertz, 2021; Rashidan et al., 2021; Santos et al., 2021) that had been found with our systematic search, we observe that they all have a much narrower scope than ours. In particular, (Alnajjar et al., 2020), surveys only papers based on humanoid robots (Abu-Amara et al., 2021), focuses only on virtual-reality intervention (Gallardo-Montes et al., 2022), classifies only apps for children and teenagers with ASD (Heath et al., 2021), is not focused on technology (Hosseinzadeh et al., 2021), surveys a smaller time frame (from 2014 to 2020) and only Internet-of-Things (IoT) technologies used in ASD diagnosis (Rashidan et al., 2021), focuses only on emotion recognition (Kohli et al., 2022b), addresses only technologies for early detection (Anagnostopoulou et al., 2020), considers only artificial intelligence techniques, and (Mertz, 2021) is not systematic and also narrowed on some specific technologies. Another difference with respect to existing surveys is in the proposed taxonomy, as we produce a purpose-based classification of the literature according to three dimensions, namely "system activity," "research purpose", and the "triad of impairment."

The rest of the work is organized as follows: in Section 3 we briefly describe how we implemented the PRISMA methodology used to select the papers in the literature and we give quantitative measures of the work. Section 4 presents the general organization of the proposed purpose-centered taxonomy, and in Sections 5, 6 and 7 we discuss the selected papers from the point of view of diagnosis versus treatment, from the point of view of the three impairments, and from the point of view of monitoring versus intervention, respectively. We finally draw the conclusions in Section 8.

2. Background

As already mentioned in the introduction, ASD is a complex neurological disorder; it involves different types of needs, which makes it difficult to create technological products or solutions that are adaptable to all of those cases. ASD presents a set of social restrictions associated with the alteration of social interaction (problems in verbal and non-verbal communication, in social and emotional reciprocity), sensory sensitivity, mental dysfunctions, and various behaviors (such as aggressiveness, self-harm, restricted interests, hyperactivity, or passivity). The symptoms of ASD already appear at an early age and remain until adulthood, thus making it difficult for such behaviors to disappear. Furthermore, the disorders mentioned above lead to other indirect impacts such as harassment, social exclusion, and school dropout. It is important to highlight that society actively coexists with ASD, as already mentioned around two out of every 100 births is diagnosed with ASD (Narzisi et al., 2018). Currently, there are some solutions that allow people with ASD to minimize problems and satisfy certain needs that improve their independence and quality of life, which include didactic, educational, behavioral, and occupational therapies. Those therapies are usually carried out at an early stage, since the detection of the disorder; in effect the early interventions in

children are the ones that most efficiently improve the social, emotional, communication and motor skills (Vivanti et al., 2014).

3. Methodology

This review of the state of the art is conducted by adopting the PRISMA methodology (Page et al., 2021). This section describes the eligibility criteria, research keywords, record identification, search results screening and analysis that we have used to implement the methodology.

For the eligibility criteria, we consider the following: i) studies that leveraged *innovative* information and communication technology and that are applied to ASD diagnosis or therapy, without restrictions on the kinds of imposed impairments; ii) diagnosis or treatment techniques that do not involve intravenous techniques, blood samples, or their derivatives; and iii) focused on children. Note that intravenous ICT solutions applied to ASD are outside the scope of this research, and so are studies that deploy existing, commercial technologies to screen or train individuals with ASD. Furthermore, we excluded papers that are primarily clinical studies and in which the focus was not on technology.

For the research keywords, we identified records that contain the keywords "Autism" AND ("technology" OR "ICT") AND ("children") AND ("DSM-5" OR "diagnos*" [diagnostic/diagnosis] OR "training" OR "therap*" [therapeutic/therapy]) AND NOT ("fertilization" OR "serum" OR "gene" OR "stem"). We considered only articles that are published within a time-frame of 15 years ranging from January 1, 2007 to December 31, 2022.

In the identification stage, we utilized three electronic databases, namely "Scopus," "IEEE Xplore," and "Web of Science," covering engineering and computer science applications. Based on the searches conducted in the online databases, 574 records were identified (Scopus = 405, IEEE Xplore = 11, WebOfScience = 158). Following this approach, documents with the same document identifier (DOI) were retrieved from different databases. At this stage, 120 duplicates were excluded from the search with respect to Scopus.

In the first screening stage, title and abstract of the remaining 454 records were analyzed to implement a first selection of papers. At this stage, records were excluded that clearly are i) surveys; ii) unrelated to ICT for ASD diagnosis/treatment; iii) clinical studies; and iv) based on existing, commercial ICT solutions. This stage eliminated 239 records, leaving 215 records for eligibility (Scopus = 196, IEEE Xplore = 3, WebOfScience = 16).

In the second stage (eligibility), we analyzed more deeply the entire text of the papers selected in the first stage. Note that, although the screening of title and abstract excluded irrelevant records, not all remaining ones could be included prior to reading the full text. Following this approach, 11 records were inaccessible, another 11 articles were written in a language different from English, 7 of them turned out to be surveys. Furthermore, in this stage, we excluded 88 records addressing the experimental use of commercial products or, being of a non-technical nature. We also excluded papers without a technical description of the used technologies. Figure 1 summarizes the PRISMA search process. Finally, 98 records (Scopus = 92, WebOfScience = 6) are left which we will study in subsequent review.

4. A new taxonomy for ICT in ASD

For over two decades, multidisciplinary research activities within the ICT domain have increased the quality-of-life of persons with ASD symptoms, and of those interacting with them. Most recent surveys, however, limit their analysis of the literature to a specific group of technologies (such as wearable devices, mobile applications, robotics, web applications, virtual/augmented reality, or others), or they limit to a very specific domain of diagnosis or intervention, with either direct or indirect reference to the category of the ASD triad of impairment defined by (American Psychiatric

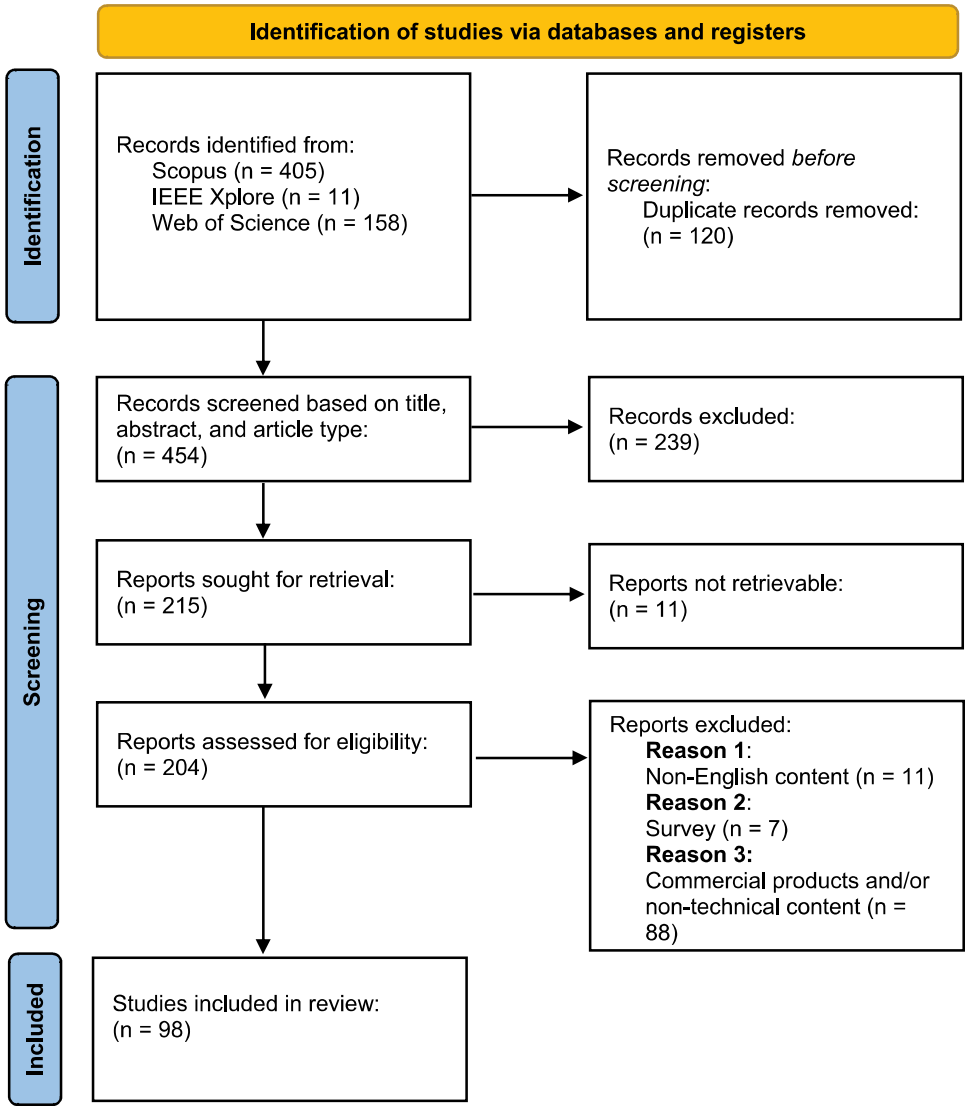


Figure 1. Flowchart showing the PRISMA selection process (Page et al., 2021).

Association, 2013) (either communication (Heath et al., 2021), social interaction (Alnajjar et al., 2020) or social behavior (Rashidan et al., 2021)).

To overcome above shortcomings, the current study follows a multidisciplinary approach on the intersection between clinical and technical point-of-views. In the article, we propose a taxonomy generated from all the ASD aspects extrapolated from the state of the art with an innovative perspective on technology, and for this reason we excluded papers using established, commercial technologies even if considered innovative from a commercial point of view.

Following this approach, we propose a three-dimensional classification matrix, as sketched in Figure 2. Each dimension corresponds to one distinct scope. Specifically, one dimension addresses the research purpose corresponding to diagnosis or treatment; the second dimension focuses on the purpose of the system in use, which is either monitoring or intervention; and the third dimension reveals the triad of impairment, i.e., either communication, social interaction, or repetitive behaviors. Table 1 reports the classification of the papers at the end of the

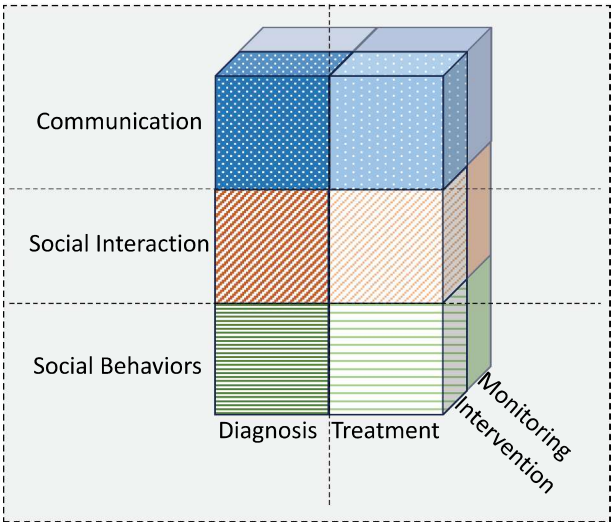


Figure 2. Proposed 3D-classification matrix spanned by research purpose, system activity, and impairment.

Table 1. Classification of the papers according to the kind of impairment addressed at the end of the eligibility phase. Note that some papers appear in more than one sub-class.

Classification	number of papers
Diagnosis (D)	14
Treatment (T)	75
Impairment: Communication	19
Impairment: Interaction	40
Impairment: Behavior	42
Monitoring (M)	41
Intervention (I)	60

eligibility phase according to each of the three dimensions. Notice that some papers fit in more than one classification while others do not fit all the classifications.

The next three sections review the literature according to the points of view corresponding to the three dimensions. Notice that the literature offers plenty of papers with respect to the triad of impairment but limited to intervention, though. In this contribution, we establish an exhaustive picture of the current ICT possibilities in the ASD domain by taking into account at least two other dimensions, namely the interdisciplinary double perspective of the diagnostic or treatment intentions plus the dichotomy of monitoring/intervention activities which each described ICT system is developed for.

The following section analyzes our classification in depth, starting from three main aspects for each research:

(1) if the objective of the study goes in the ASD diagnosis or treatment direction
(2) if the field of impairment addressed by the ICT intervention could be attributed to the communication, the social interaction or to the behavioral disorder domain
(3) if the ICT systems are implemented to execute monitoring or response activities in order to achieve the goal in the previous identified areas (points 1 and 2).

Starting from the current state of the art in Tables 2–4, we subsequently extract and map the respective research item on the three dimensions, spanning our taxonomy matrix in Figure 2.

Table 2. Research papers related to ICT for communication ranging from 2007 to 2022. The purpose might be either Diagnosis (D) or Therapy (T). The activities refer to Monitoring (M) and/or Intervention (I). ML = machine learning.

Reference	Purpose	Activity	Technology	Control group	Test group
(Rahman et al., 2011)	T	I	Gamification	N/A	10
(Venkatesh et al., 2012)	T	I	Digital world	N/A	31
(Lin et al., 2013)	T	M	Digital world	300	35
(Alessandrini et al., 2014)	T	M	Digital reality	N/A	4
(Macpherson et al., 2014)	T	I	Digital world	N/A	5
(Halabi et al., 2017)	T	M	Digital reality	7	3
(Whitehouse et al., 2017)	T	I	Digital world	39	41
(Muharib et al., 2019)	T	M	Digital world	N/A	3
(Schafer et al., 2019)	T	I	Digital world	N/A	15
(Egido-Garcıéa et al., 2020)	T	I	Robotics	N/A	5
(Louie et al., 2020)	T	I	Robotics	N/A	3
(Liu et al., 2021)	T	I	Digital world	N/A	N/A
(Boyle & Arnedillo-Sanchez, 2022)	T	M	Digital world	N/A	5
(Castellanos et al., 2022)	T	I	Digital world/ML	N/A	N/A
(Gevarter et al., 2022)	T	I	Digital reality	N/A	2
(Güler & Erdem, 2022)	T	I	Digital world	N/A	3
(Hao et al., 2022)	D	M	ML	N/A	N/A
(Lee et al., 2022)	T	M/I	Digital reality	N/A	N/A
(Morales et al., 2022)	T	M	IoT	N/A	20

5. Diagnosis vs. treatment

As already discussed earlier, some persons with ASD might have limited communication ability or easily get upset by changes to routine. They might find it difficult comprehending other individuals' emotions or, show repetitive behavior. Diagnosis is concerned with the act of identifying the exact cause for above behavior. Currently, there is no blood test, imaging method, or genetic screening technique available for diagnosis of ASD. Instead, trained clinicians qualitatively evaluate child development during toddler stage. Though the American Psychiatric Association, 2013 published a guideline, a substantial amount of training is required to become proficient in diagnosing ASD (Louie et al., 2020). Due to its subjectivity, a different diagnosis might occur from different clinicians. Hence, a quantitative standard is required at a certain level of predefined precision to properly score ASD. Pioneering data-driven Communication and Information Technologies (ICT) solutions help to screen the disorder in children earlier than the current average age of diagnosis (Caruso et al., 2020). The difficulty in making reliable judgments about the presence or absence of symptoms and their severity is still underscored in research.

Nevertheless, there are a few promising research threads toward reliable *diagnosis*:

- Digital world
- Internet-of-Things,
- Robotics,
- Digital reality.

All of above techniques go hand-in-hand with advanced machine learning algorithms for ASD classification.

The *digital world* is an umbrella term for traditional applications for PC, smart phone/tablet, and the web browser. In semiautomatic mode, the healthcare professional performs clinical diagnostic reasoning based on the experimental outcome (J. Chen et al., 2019). With the advance in technology, the ICT tools in the digital world have become automatic, i.e.,, have decision-making competence without the need of a human (Simeoli et al., 2021; W. Zhao & Lu, 2020).

The Internet-of-things (IoT) paradigm refers to sensors embedded in physical objects along with processing capability and software that connect to the internet. Focusing on ASD, IoT wearable devices are capable of sensing data related to emotion, stereotyped behavior, and stress states of the

respective candidate. This includes heart rate, galvanic skin response, blood volume pulse (Iakovidou et al., 2020) as well as acceleration and orientation (Bondioli et al., 2021). All these sensors produce massive datasets that are aggregated in the cloud that can leverage machine learning as well as deep learning.

Over time, powerful machine learning has been developed capable of providing complex ASD diagnosis at an accuracy above 90%. (W. Zhao & Lu, 2020) deploy deep convolutional neural networks to classify various (static) emotions (Kojovic et al., 2021; Varma et al., 2022); use Long short-term memory (LSTM) neural networks, to estimate the behavior evolution over time (Hao et al., 2022); showed that kernel extreme learning machine, fed with real-world screening data of candidates from the National Institute of Health Research, is capable of predicting the presence of ASD. In any case, with sufficient training data, machine learning classifiers show high sensitivity.

In the field of robotics, the work of (M. Chen et al., 2021) shows that social robots can provide consistent, reliable actions ensuring that identical stimuli are presented in an arbitrary diagnostic session. In this context, social robots may aid in diagnosis by providing consistent behavioral evaluations and standardized stimuli.

Digital reality, referring to a wide spectrum of technologies including augmented reality (e.g. smart glasses), virtual reality, and mixed reality, and the metaverse can be used to establish social interactions between the candidate and other individuals during which artificial intelligence detects repetitive body movements, typical for ASD (Kojovic et al., 2021; Raya et al., 2020).

Moving toward *treatment* in the same dimension of the classification matrix, we find research work aiming at reducing the diagnostic symptoms that interfere with quality of life. Most of the research threads in the literature are concerned with this class. During the last two decades, numerous ICT tools ave been developed , operating on:

- Social competences (communication, interaction, behavior). Computer simulation software encourages desired and discourages undesired behaviors using Discrete Trial Training (DTT) (Kientz et al., 2007; Yun et al., 2016). ICT-based Pivotal Response Training would be another option, but this is still an open research topic at the time of writing. Anxiety therapy in fact-to-face communication has been deeply investigated within the field of virtual reality (Tan et al., 2022).
- Skill development. In the digital world, there are a large number of mobile learning apps for individuals with ASD, such as going to school, crossing a street, preparing for a bus trip (Almazaydeh et al., 2022), going to the dentist (Narzisi et al., 2020), consulting a medical doctor (De Urturi et al., 2011), etc.
- Education. Here, the Treatment and Education of Autistic and Related Communication-Handicapped Children (TEACCH) approach, based on consistency and visual learning, plays an important role. In this context, the design of assistive technology must facilitate physical accessibility (limited mobility of individuals with ASD), cognitive accessibility (attention, memory, comprehension, making choices, language, and literacy) and sensory accessibility (correct perception of the environment) (Cañete et al., 2021). The digital world helps the children with ASD develop language and literacy (Boyle & Arnedillo-Sanchez, 2022), augmented and virtual reality technology improves engagement and concentration time (Amara et al., 2022), attention, vocabulary and imitation (Esposito et al., 2017).

Finally, it is worth pointing out the futuristic metaverse-based social skills training program that intervenes in the behavior of the virtual world game played by the individuals with ASD based on their sensed biomarkers in real-time (Lee et al., 2022). The metaverse is still emerging so that there is no consistent definition of architecture yet. Jon Radoff proposed a seven-layered architecture from the bottom to the top ranging from infrastructure, human interface, decentralization, spatial computing, creator economy, discovery, and experience through social gaming, social e-sports, shopping (Radoff, 2021).

6. The triad of impairment

Individuals with autism do not always show all symptoms at the same level of severity. Some symptoms may not occur at all. However, there are five diagnostic criteria according to the 5th-edition of the Diagnostic and Statistical manual of Mental disorders (DSM-V) by the American Psychiatric Association that categorize the different traits by which ASD manifests itself. The diagnostic criteria are (American Psychiatric Association, 2013):

(A) Autistic communication and social interaction across multiple contexts. This includes deficits in social-emotional reciprocity, deficits in nonverbal communication, and deficits in developing, maintaining, and understand relationships. Persons with ASD have difficulties with interpreting both verbal and non-verbal language like gestures or tone of voice. Many have very literal understanding of language, and think people always mean exactly what they say. Others may not speak, or have fairly limited communication using speech. They will often understand more of what other people say to them than they are able to express, yet may struggle with vagueness or abstract concept. They may find it hard to form friendships. Some may want to interact with other people and make friends, but may be unsure how to go about it. They often have difficulty with recognizing or understanding others' feelings and intentions as well as expressing their own emotions.
(B) Repetitive patterns of behaviors (stimming, sameness, special interests, and sensory sensitivities). Persons with ASD may not be comfortable with the idea of change, may also experience over- or under sensitivity to sounds or textures, tastes, smells, light, colors, temperatures or pain.
(C) Symptoms must be present since childhood. Autism is lifelong, and present since/before birth.
(D) Degree to which autism affects daily functioning. The symptoms cause clinically significant impairment in social, occupational, or other important areas of current functioning.
(E) Traits not better explained by intellectual disability. Intellectual disability and autism spectrum disorder frequently co-occur. Communication skills should be below that expected for general developmental level.

Following the DSM-V manual, the triad of ASD impairment is commonly defined as the intersection of communication, social interaction, and social behavior.

Subsequently, we focus on ICT tools for the ASD triad of impairment in the literature using the PRISMA methodology. When the clinical severity of ASD is mentioned, we will explicitly bring it up in the description.

6.1. *Communication*

Communication refers to the way in which individuals use verbal and non-verbal language to share experience, thoughts, and emotions.

Individuals with ASD that have speech and language disorders face difficulties in interpreting and interacting with the world when communicating (Rahman et al., 2011). Since the 1970s, numerous experiments have been conducted involving ICT systems that target different levels of ASD functioning. As shown in Table 2, digital tools for improving communication abilities mainly belong to two classes:

- ICT tools for visual languages that communicate through visual elements,
- ICT tools for logopedics to correct speech and language defects and disorders in communication.

Table 2 lists ICT technologies with purpose and system activity, according to the investigated impairment, and sorted by publication year in ascending order. The last two columns list the number of children in the control group and in the test group.

6.1.1. *Visual languages*

In some cases, children with ASD are non-verbal or have limited verbal expression. As they are unable to express their feelings and wishes, they may communicate with Augmentative and Alternative Communication (AAC) technologies. Before speech and language therapy is possible, ICT has to provide concrete tools for immediate use to facilitate the expressions of the children with ASD . Following this approach, several studies test and promote digital platforms that make easier, more immediate and portable tools for AAC. The most prevalent AAC techniques are either Picture Exchange Communication System (PECS) visuals or line drawings.

A good number of children with ASD cannot produce a full sentence. (Rahman et al., 2011). address this issue by deploying AAC as a medium for instruction. The proposed interactive learning game is capable of teaching low functioning children with ASD to utter intelligible sounds for a given image on the screen in an autonomous fashion. A speech engine converts voice to text that is compared with the metadata of the displayed image.

Considering a more advanced ICT system, (Castellanos et al., 2022) has developed a speech therapy system composed of a smartphone application capable of making and classifying pictures from surrounding objects or loading PECS from a gallery. The images are translated to speech, for the user to pronounce. The user repeats the phrases/sentences, the voice is recorded, translated to text, and compared with the original.

Finally, (Gevarter et al., 2022) use an AAC application on a smartphone, to create multi-symbol messages. The study involved matrix training, to teach learners a subset of possible word or stimulus combinations (e.g., dog eat, baby hug, bear kiss) with the intention that the teaching of these targets will generalize to untrained but similar targets (e.g., dog hug, baby kiss, bear eat). Two pilots could indeed increase the number of multi-symbol AAC messages in play contexts.

6.1.2. *A logopedic approach*

Most of the ICT tools for logopedic *intervention* have their roots in classical software applications for PC, tablet and the web browser.

The tablet application of (Venkatesh et al., 2012) with multi-touch interface was one of the first in this field. In the absence of a trained therapist, the automated multimedia application “wait-list program” teaches toddlers words, their relations, and utterances among other tasks. (Macpherson et al., 2014) examined the effects of a portable video modeling intervention on the verbal compliments and complement gestures. Phrases and gestures were modeled at an exaggeratedly slow pace of ca. 20 s duration. Five pilot low-functioning children with ASD increased their verbal complements. The Australian team (Whitehouse et al., 2017) developed the tablet-based application Therapy outcomes by you (TOBY) with a build-in reward system, to actually complement early behavioral intervention. Instead, the 8 pilot children significantly improved on the Total Words Understood scale of the MacArthur-Bates Communicative Development Index after an intervention of 6 months. Finally, it is worth pointing out the smartphone based (animated) social story maps by (Güler & Erdem, 2022), to improve communication skills and listening comprehension skills of participants with ASD.

Social assisted robots (SARs) for education can have positive impact on learners. Their appearance is often humanoid or zoomorphic, to have a meaningful social impact. They must be able to interpret not only human speech, but also body language using computational psychology and advanced sensors to automatically recognize nonverbal cues. Following this approach, the SAR by (Egido-Garcıéa et al., 2020) was programmed with the modules i) reading comprehension; ii) dictations, stories and vocabulary, improvement of oral comprehension; iii) articulation and phonetic-phonological pronunciation; iv) phonological awareness and phonetic segmentation; v) literacy

skills. A preliminary study with five children indicates a positive impact on the formulation of questions and answers. Independently (Louie et al., 2020), developed a humanoid for listening comprehension intervention in place of a human therapist by reading passages from electronic books. All the children participating in the intervention improved in the skill being taught by the robot.

For color cognitive training of children with ASD and to monitor speech at the same time (Liu et al., 2021), presents the technical concept of an interactive training tool based on acoustic-optical interaction. A voice recognition model judges the child's response and vocalizes excitation sounds through speakers.

Moving to dichotic listening, the software application CAPDOTS in (Schafer et al., 2019) interaural and adaptive lead/lag timing differences to improve binaural integration skills of different speech stimuli (words, numbers, and syllables). However, a test on 15 high-functioning children with ASD indicates that time commitment that was required for the participants and families was a substantial barrier.

So far, we have considered ICT tools for intervention. However, there are also quite a few interesting solutions available for *diagnostic* purposes.

For example, the web application by (Lin et al., 2013) assesses language skills of Taiwanese children with ASD. The test consists of six exercises: decoding, homographs, auditory vocabulary comprehension, visual vocabulary comprehension, auditory sentence comprehension, and visual sentence comprehension. (Halabi et al., 2017) rely on immersive virtual reality with verbal/nonverbal input interaction in high-functioning children with ASD. The virtual world comprises a school, a student, and a teacher avatar. Different scenarios at school are emulated. The tablet application by (Muharib et al., 2019) deploys backward chaining and speech-output technologies, to enhance functional communication skills. The app was successfully tested on three low-functioning children with ASD. Most recently (Boyle & Arnedillo-Sanchez, 2022), developed a language development and literacy application, to support letter identification and matching sounds with images of common objects. The research followed a participatory design approach alongside the children with ASD.

Focusing on attention training (Alessandrini et al., 2014) describes a prototype of an audio-augmented paper for low-functioning children with ASD, to build cooperation to attention control, flow control, and using the children's own voices to foster attention. The social stories intervention was verified on four children.

Finally, it is worth pointing out one research paper that addresses breathing training to reduce stress in children with ASD (Morales et al., 2022): proposes an IoT wearable embedded in ambient intelligence. Physiological data (electrocardiography, photoplethysmography (PPG), pulse transit time) and adherence data (eye tracking) and environmental data (temperature, light, and sound) are sent up to the cloud to get processed and experience personalization. The result is generated to surround the user with elements of sound (water, fire, air, etc.) in an adaptive fashion. Data from 20 children in Mexico were used to train the personalization module as a function of breathing amount and frequency.

Finally, it is worth pointing out that metaverse technology is currently changing the concept of communication in both, ASD and normal individuals (Lee et al., 2022). In a virtual 3D environment using artificial intelligence techniques, the metaverse is a combination of communication and digital twin integration. Communication among peers occurs via digital body language built on trust and connection independent of the distance. There is no need for face-to-face communication anymore so that the barrier vanishes between individuals with ASD and others.

6.2. *Social interaction*

Social interaction is the way in which individuals influence each other during face-to-face encounters. The challenge for individuals with ASD is to correctly predict and interpret others' behavior. The American Psychiatric Association provides diagnostic criteria (American Psychiatric

Association, 2013). Specifically, individuals with ASD may be unable to interpret another person's mental state and emotion based on immediately available information or observations such as facial expressions or tone of voice. They may also face difficulty with predicting or explaining another person's actions by inferring their mental state. Without intervention, social and emotional deficits can affect the overall quality-of-life of individuals with ASD in numerous ways such as social rejection and isolation. Social and emotional skill deficits can also contribute to academic and occupational under-achievement as well as mental health problems (Baron-Cohen & Hadwin, 1999).

ICT is one approach to address many of these barriers. Compared to traditional instruction, its digital form provides a "protected" custom environment that is predictable and free from distracting stimuli. Innovative ICT-based interventions allow for increasing task engagement and decreasing escape maintained challenging behavior in individuals with ASD.

Modern ICT systems have a lot of potential for intervention in social interaction such as emotion recognition, social pragmatics rules (conflict management, initiating interactions, responding to others, developing peer relationships, and so forth) and social interaction in everyday life (classroom settings, medical examination, etc.) The literature highlights three main areas of interest:

(1) Digital tools and resources for collaborative skill development;
(2) ICT systems for emotion recognition skills;
(3) Digital approach to develop daily living skills.

Table 3 reports a summary of the papers related to ICT for diagnosing/treating social interaction. The last two columns indicate the number of participants in the control group and in the test group. Most of the available tools have their application in the therapy, though.

6.2.1. *Collaborative skills*

To train *collaborative skills* to children with mild-to-medium ASD, a number of SARs have been developed, capable of carrying out complex actions automatically. Such robots process physical perceptions by digital means, operate semi-autonomously physical parts of themselves, manipulate their environment, and show intelligent behavior including certain cognitive and/or social abilities. Initially, those social robots had only limited functionality. For example, the small creature-like robot "Keepon" by (Kozima et al., 2009) is designed for simple, natural, nonverbal interaction with children, intuitively and comfortably conveying the robot's expressions of attention and emotion. (Robins & Dautenhahn, 2014) equipped the commercially available humanoid robot "Kaspar" (University of Herdfortshire, UK) with tactile capabilities. It allows individuals with ASD to explore touch in a way that can be completely under their control. (Wood et al., 2021) deployed the same robot to involve the child in an imitation game in a closed-loop design. The work of (Özcan et al., 2016) presents a "transitional wearable companion" for social skill development in children with ASD. Transitional objects (puppets, blankets, etc.) offering a soft touch with an embedded mechatronics system design can react to the actions of the child by light, sounds, vibrations, etc. (Valadão et al., 2016) designed a mobile robot with a special costume that displays multimedia contents, to interact with children with ASD. A mediator controlled the robot's movements. Four out of five children improved their social skills during a pilot study. The autonomous humanoid by (Zheng et al., 2016) recognizes gestures and provides dynamic feedback in real-time, to teach toddlers with ASD imitation skills. (Del Coco et al., 2018) integrate multiple visual cues involving facial expression recognition, landmark extraction, and gaze estimation. Experiments with eight children with ASD result in precision and recall of more than 90%. The spherical robot "COLOLO" by (Nunez et al., 2018) teaches children with ASD a very important social interaction technique, namely turn-taking through play. To improve social responses and behaviors of children with ASD, (Feng et al., 2022) programmed the commercially available humanoid robot NAO (Aldebaran Robotics, France), to be capable of interactively teaching children with ASD play Xylophone. Electrodermal activity testing on 9 children with ASD clearly shows music-induced emotions. Six participants, i.e.,, 70%, could

Table 3. Research papers related to ICT for social interaction ranging from 2007 to 2022. The purpose might be either Diagnosis (D) or Therapy (T). The activities refer to Monitoring (M) and/or Intervention (I). ML = machine learning.

Reference	Purpose	Activity	Technology	Control group	Test group
(Kozima et al., 2009)	T	M	Robotics	N/A	27
(Yen et al., 2010)	T	M	Digital world	N/A	N/A
(Ben-Sasson et al., 2012)	T	I	Digital world	N/A	12
(Goodrich et al., 2012)	T	I	Robotics	N/A	2
(Venkatesh et al., 2012)	T	I	Digital world	N/A	8
(Bekele et al., 2013)	T	I	Robotics	6	6
(Lahiri et al., 2013)	T	I	Digital reality	N/A	8
(Modugumudi et al., 2013)	T	I	Digital reality	N/A	10
(Robins & Dautenhahn, 2014)	T	I	Robotics	N/A	36
(Özcan et al., 2016)	T	I	IoT	N/A	N/A
(Valadão et al., 2016)	T	M	Robotics	5	5
(Wade et al., 2017)	T	M	Gamification	12	12
(Zheng et al., 2016)	T	I	Robotics	10	12
(Zheng et al., 2017)	T	M	Digital world	10	10
(Daniels, Haber, et al., 2018)	T	M/I	IoT	20	23
(Daniels, Schwartz, et al., 2018)	T	I	IoT	N/A	14
(Del Coco et al., 2018)	T	I	Robotics	N/A	8
(DiNuovo et al., 2018)	T	M	ML	N/A	6
(Hachisu et al., 2018)	T	M	IoT	N/A	6
(Nunez et al., 2018)	T	I	Robotics	N/A	4
(Porayska-Pomsta et al., 2018)	T	I	Digital reality	6	15
(H. Zhao et al., 2018)	T	M	Digital reality	12	12
(Mairena et al., 2019)	T	I	Gamification	N/A	15
(Saleh, 2019)	T	M	Robotics	N/A	N/A
(Voss et al., 2019)	T	I	Digital reality	31	71
(Terlouw et al., 2020)	T	I	Gamification	19	28
(W. Zhao & Lu, 2020)	D	M	Digital world/ML	10	10
(M. Chen et al., 2021)	D/T	M	IoT/Robotics	N/A	N/A
(Douglas et al., 2021)	T	M	IoT	N/A	3
(Jialiang et al., 2021)	T	I	Digital reality	6	6
(Lang et al., 2021)	T	M	Robotics	N/A	5
(Ma & Yang, 2021)	T	I	Gamification	10	10
(Nie et al., 2021)	T	I	Digital reality	N/A	6
(Pavez et al., 2021)	T	I	Digital world/ML	N/A	N/A
(Wedyan et al., 2021)	T	I	Digital reality	N/A	12
(Wood et al., 2021)	T	I	Robotics	N/A	4
(Feng et al., 2022)	T	M	Robotics	7	9
(Hao et al., 2022)	D	M	ML	N/A	N/A
(Hocking et al., 2022)	T	I	Gamification	N/A	10
(Varma et al., 2022)	D	M	Digital reality/ML	27	68
(Wan et al., 2022)	D	M	Digital world/ML	N/A	10

complete motor control and turn-taking tasks. Finally, the question arises whether the child actually pays attention to the robot during a therapy session. (DiNuovo et al., 2018) addressed this issue by developing a deep neural network for engagement classification.

Moving to augmented reality, (Pavez et al., 2021) present an intelligent mirror comprising a camera, the small single-board computer Raspberry-Pi and, an LCD screen. A Convolutional Neural Network (CNN) analyzes the captured images and compares the result with the one that the patient should perform and shows in its face the meaning of the emotion they are trying to imitate. The authors utilized the pre-trained VGG16 and ResNet50 to perform their analyzes. Clearly, accuracy of above CNNs depends on amount and quality of training images.

Virtual environments allow users to interact in real-time with a three-dimensional computer-based world, incorporating impressive graphics and design. Following this approach for therapy (Lahiri et al., 2013), monitors eye-gaze in real-time, to engage some 80 participants with high functioning ASD during virtual reality-based interaction in an adaptive fashion. For this purpose, 24 social tasks were developed in which avatars narrated personal stories to the participants. The participants were asked to extract information from the avatar using a bi-directional conversation

module with varying levels of interaction difficulty. (Hocking et al., 2022) follow a similar approach to assess motor skills in individuals with ASD.

Collaborative virtual environments (CVE) are another class of ICT tools that help children with ASD perceive the effect of emotion expression. (Modugumudi et al., 2013) performed a clinical study with 10 children with ASD located in remote locations but who interacted with each other in the CVE. Electroencephalography (EEG) and electrooculography (EOG) recordings after the intervention show a significant change in the group of individuals with ASD in recognizing the emotions with respect to the control group. Mentioning another example (H. Zhao et al., 2018), developed a virtual environment called "hand-in-Hand" that is capable of supporting naturalistic social interaction, promoting communication within game play, and gathering objective data on user's performance and communication in real time. Twelve children with ASD improved their cooperation in game play.

The development of serious games, a sub-genre of serious storytelling outside the context of entertainment, is another major research area in this context. Following this approach for therapy, (Ben-Sasson et al., 2012) found great potential in guiding children with high functioning ASD to complete a mutual goal after they had played 12 technological touch activated collaborative puzzle games. In another study (Porayska-Pomsta et al., 2018), "low functioning" autistic children in several schools across the UK were exposed to the single user technology-enhanced learning environment ECHOES that utilizes an artificially intelligent virtual character as a social partner in the fields of sharing of attention with others, turn-taking, initiating, and responding to bids for interaction. The study shows a significant increase in the proportion of children's responses to the human social partners. The work of (Mairena et al., 2019) shows that video games involving the whole body elicit more social initiation. Next, it is worth noting the interactive gaming platform "it's me" by (Terlouw et al., 2020), where "high-functioning" children with ASD may create their own personal digital comics, to serve as boundary objects for transformative change, and to facilitate and enact a horizontal interaction structure between high-functioning children with ASD and their peers. The tools sound promising. However, clinical tests do not seem to be available yet.

Paying *joint attention* to an object and a person during a social interaction is another challenge for individuals with ASD. A number of Socially Assistive Robots (SARs) were developed for this purpose. The approach proposed by (Goodrich et al., 2012) foresees a therapist-controlled SAR that initiates a joint attention scenario while the child plays with a toy. The robots await response of the child, reply, and display an emotion according to the input by the human. The humanoid by (Bekele et al., 2013), operating on its own, intelligently adapts itself in an personalized manner to generate prompts based on cues from the child's head movement. The robot was tested on six children with ASD. It turned out that the children focused on the robot 50% longer than on the human therapist. Moving to ICT involving augmented reality (Nie et al., 2021), presents a Kinect-based immersive Computer-mediated Caregiver–Child Interaction system that autonomously interacts with the ASD individual. A feasibility study with six children with ASD indicated that the proposed system has potential to create situations in which children are likely to initiate joint attention tasks without creating additional stress for the caregivers.

To enhance dyadic collaboration (Wade et al., 2017), developed the game and data acquisition platform Dyad-Operated Social Encouragement (DOSE). In a pilot study, 12 dyad-comprised children with ASD were monitored. Finally, the smartphone application by (Varma et al., 2022) obtains gaze information without eye-tracking hardware. The work shows that semistructured gameplay videos collected on mobile devices reveal specific regions of gaze fixation.

6.2.2. *Emotion recognition*

Early software applications had the capability of recognizing human emotional state only by simple tools, such as an embedded camera (Yen et al., 2010). In the same time, they work autonomously without the need for human intervention. For example, (Zheng et al., 2017) designed an autonomous

web-based social training system allowing real-time attention inference of the participant through gaze tracking using a distributed array of cameras.

Another approach is to allow an interactive experience in a real-world environment supported by ICT. Augmented reality face recognition features empower children with ASD to recognize their associated expressions (Wedyan et al., 2021). Microsoft Kinect, a line of motion sensing input devices, has been extensively used for design of interactive games during the past decade. Following this approach, the researchers built an augmented reality application using the Unity platform, to detect facial expressions and their description (happiness, sadness, surprise, fear, disgust, and anger) for the acting users as well as their playmates from the sensors and to display the result on the screen. By selecting the right expressions, the users progressively learned to cope with the emotional state of their playmate. Instead, (Daniels, Haber, et al., 2018) and (Daniels, Schwartz, et al., 2018) deployed Superpower Glass, a machine-learning-assisted software system that runs on Google Glass, together with a smartphone application designed for use during social interactions. After the test, parents of all 14 test subjects reported increased eye contact and greater social acuity. The work of (Voss et al., 2019) follows a similar approach. Finally, (Ma & Yang, 2021) use Kinect's image acquisition, limb tracking, motion recognition, and voice recognition as input to four somatosensory games for children with ASD, to train daily life skills. A 6-month test campaign on Chinese children demonstrated the efficacy of this series of games.

The evolution of IoT technology generates nwearable applications in the field of ASD. For example, the smart headband FaceLooks by (Hachisu et al., 2018) uses infrared communication, to visualize face-to-face behavior as flashing colors on the headband. Experiments during lunch time on six children with ASD with moderate intellectual disability showed that the average face-to-face interaction between them and their teachers increased by a factor 2, over two sessions. (Douglas et al., 2021) validated social proximity (face-time and frontal proximity) using ultrasound-based wearable sensor technology. Finally, the AI-based cognitive wearable fashion clothing item by (M. Chen et al., 2021) recognizes facial expression, body movement, and verbal communication. This data is fed into a reinforcement machine learning model, to revise the emotional state of the child. The database that is generated can also be used for diagnosis purposes.

With the help of IoT, humanoid robots have become able to understand and convey emotions by measuring the current arousal state of the child with ASD (Lang et al., 2021). More advanced humanoids deploy convolutional neural network-based machine learning algorithms that are aware of facial expressions, to guide children with ASD through social interactions (Saleh, 2019).

When the sensed data is fed into an LSTM neural network, mild ASD can be successfully predicted. The authors in (W. Zhao & Lu, 2020) feed a deep CNN with facial expression images of Chinese children from high-definition cameras, to classify the facial expressions angry, disgust, fear, happy, sad, surprise, and neutral with an accuracy of 81%. These CNNs were trained by the publicly available databases FER2013 and CK+. The work in (Wan et al., 2022) follows a similar approach.

6.2.3. *Social interaction in daily life*

To manage social interaction in daily life, quite a few software applications have been developed. For example, the smartphone application by (Venkatesh et al., 2012) comprises the play routines "Matching food," "What's in the bag" or "Let's go shopping." The routines adapt automatically to the child's performance. (Jialiang et al., 2021) designed a virtual reality environment to support auxiliary treatment of children with ASD. Through experiments, children with autism have improved their hands-on ability, social skills, and physical coordination.

6.3. *Social behavior*

Social behavior is commonly defined as all behavior that influences other members of the same genre. The social behavior of individuals with ASD is characterized by

- restricted and repetitive behaviors
- hyper anxiety disorder in 40% of the cases

according to DSM-V, Criterion B (American Psychiatric Association, 2013). For stereotyped patterns, behaviors may be verbal or nonverbal, fine or gross motor-oriented, as well as simple or complex. Common examples of stereotyped behavior are hand flapping, body rocking, toe walking, spinning objects, sniffing, immediate and delayed echolalia, and running objects across one's peripheral vision.

Table 4 summarizes the research papers related to social behavior along with their application purpose, type of activity, applied technology and number of participants in the control and test groups.

6.3.1. *Restricted and repetitive behaviors*

Diagnosis: The rapid development and implementation of IoT-based technologies have allowed for various possibilities for ICT assisted ASD diagnosis tools. Some 15 years ago, the prototype of (Kientz et al., 2007) comprised three wireless accelerometers only, to monitor stimming in ASD.

Table 4. Research papers related to ICT for social behavior from 2007 to 2022. The purpose might be either Diagnosis (D) or Therapy (T). The activities refer to Monitoring (M) and/or Intervention (I). ML = machine learning.

Reference	Purpose	Activity	Technology	Control group	Test group
(Kientz et al., 2007)	T	M	IoT/ML	N/A	N/A
(Palsbo & Hood-Szivek, 2012)	T	I	Robotics	N/A	18
(Artoni et al., 2013)	T	I	Digital world	N/A	N/A
(Cai et al., 2013)	T	I	Digital reality	N/A	15
(Escobedo et al., 2014)	T	I	IoT	N/A	18
(Bai et al., 2015)	T	I	Digital reality	N/A	12
(Tentori et al., 2015)	T	I	Digital reality	N/A	N/A
(Yun et al., 2016)	T	I	Robotics	N/A	8
(Caro et al., 2017)	T	I	Gamification	N/A	7
(DiPalma et al., 2017)	T	M	IoT	N/A	5
(Kuriakose & Lahiri, 2017)	T	I	Digital reality	N/A	9
(Egger et al., 2018)	D	M	Digital reality/ML	N/A	1756
(Shapi'i et al., 2018)	T	I	Digital reality	N/A	N/A
(Cao et al., 2019)	T	M/I	Robotics	N/A	11/21
(J. Chen et al., 2019)	D	M	Gamification	51	40
(Johnston et al., 2019)	T	M	Digital reality	N/A	29
(Mruzek et al., 2019)	T	M/I	IoT	16	16
(Préfontaine et al., 2019)	T	I	Digital world	N/A	11
(Caruso et al., 2020)	D	M	Multimedia/ML	53	50
(Faria et al., 2020)	T	M	IoT	N/A	30
(Iakovidou et al., 2020)	D	M	IoT/ML	N/A	10
(Javed et al., 2020)	T	M	Robotics	13	5
(Jialiang et al., 2021)	T	I	Digital reality	6	6
(Narzisi et al., 2020)	T	I	Digital world	N/A	59
(Puli & Kushki, 2020)	T	M	IoT	N/A	15
(Raya et al., 2020)	D	M	Digital reality	25	24
(Beaudoin et al., 2021)	T	M	IoT/Robotics	N/A	2
(Bondioli et al., 2021)	D	M	IoT/ML	25	25
(Cañete et al., 2021)	T	I	Gamification	N/A	N/A
(Kojovic et al., 2021)	D	M	Digital reality	34	34
(Nguyen et al., 2021)	T	I	IoT	N/A	28
(Sotoodeh & Taheri-Torbati, 2021)	T	I	Digital reality	24	24
(Simeoli et al., 2021)	D	M	Digital world/ML	30	30
(Teo et al., 2021)	T	I	Gamification	10	10
(Tunc¸genc¸ et al., 2021)	T	M	Gamification	21	27
(Almazaydeh et al., 2022)	T	I	Digital reality	N/A	9
(Amara et al., 2022)	T	I	Digital reality	N/A	18
(Hao et al., 2022)	D	M	ML	N/A	N/A
(Shahab et al., 2022)	T	I	Digital reality	N/A	5
(Tan et al., 2022)	T	M	Digital reality	N/A	5

The three sensors could be placed on the left hand, on the belly and the right foot, respectively. However, there were not yet available proper machine learning algorithms capable of classifying the vast amount of sensed data. Innovative communication technologies along with advanced in artificial intelligence open up new possibilities. (Bondioli et al., 2021) developed a smart toy with a number of wireless sensors, including accelerometer, gyroscope, and magnetometer. These sensors relate the movement patterns of the child to an electric signal. A cloud server aggregates and processes the sensed data and feeds the result into (recurrent) neural network assisting in the decision of a healthcare professional. To automate prediction of ASD for atypical nonverbal behavior manifestation (Kojovic et al., 2021), recorded videos which feature social interactions between a candidate child and an adult, fed the result to a pose skeleton estimator and then, to an LSTM neural network that can recognize a number of complex behavioral phenotypes. This kind of augmented reality-based diagnosis has an accuracy of 81% ($n = 34$ children with ASD). Though published earlier, The pose skeleton estimator by (Raya et al., 2020) is capable of detecting repetitive body movement in real-time with the aid of a low-complex support vector machine classifier.

Although they do not replace standard health care, professional smartphone applications have become popular, to give a first insight into possible ASD behavior. Following this approach (Egger et al., 2018), embeds a face detection algorithm while the child watches some video. Using tools from computer vision, automatic behavioral coding of these streams analyze children's emotions and behaviors and thus, the level of ASD. 1756 families participated, to support this research. (J. Chen et al., 2019) designed computer games that indicate the development level of ASD, and tested them on 91 children. The games were based on the theoretical frameworks ToM, executive functioning, and the Central coherence theory (Happé & Frith, 2006). Finally, we want to point out the smart tablet by (Simeoli et al., 2021) that uses touch screen sensor technologies, to capture detailed information about children's motor patterns with the help of supervised machine learning. Finally, (Caruso et al., 2020) developed MOVIDEA, a semi-automatic software to analyze video recordings of spontaneous movements of young children aimed at the early detection of ASD.

Children with ASD are typically have worse hand-eye coordination. To tackle this issue (Shapi'i et al., 2018), proposes a serious game using Kinect technology that senses eye gaze and hand movements in touching an object. The game is built on an avatar that can retain the children's attention as the game progresses and on rewards in the form of points and additional game time. Unfortunately, only a prototype has been developed, so far. To improve eye-body coordination, exergames could support motor therapies as they combine game technology with exercise activity. A 7-week study with children having severe ASD indicates that aimless limb movements could be removed and attention improved at the same time (Caro et al., 2017).

Treatment: For treatment of attention in ASD, play therapy has been an importance practice since the beginning. In directive play therapy, the therapist sets specific interventions and goals. For example, the virtual 3D-dolphinarium in (Cai et al., 2013) is an application of Kinect technology (Tan et al., 2022). follows a similar approach, to design a serious game emulating the crossing of a street.

To engage children with immersive visualization, virtual dolphins respond to the hand gestures of the child with ASD. A pilot study with 15 very low-functioning children with ASD made 6 of them willing to learn. When equipped with head-mounted displays, the children with ASD dive in an Immersive Virtual Realities (IVR) that can be used to enhance reliance on body-based information (Valori et al., 2020). To engage children with immersive audio, in contrast (Johnston et al., 2019), created an environment for interactive intervention, aimed at examining auditory spatial attention and sound localization ability of children with ASD. A pilot study with 29 participants listening to binaural-based spatial audio showed higher spatial attention toward target auditory events. The virtual reality system by (Jialiang et al., 2021) improves hands-on ability through active engagement rather than typical classroom lectures, as an experiment with 12 children with ASD shows.

Dance movements in a videogame in combination with Kinect sensor technology can also be used to train imitation skills in children with ASD (Tunc¸genc¸ et al., 2021). Another application of Kinect can be found in (Amara et al., 2022). Here, the sensed signals are used to merge gesture and voice of the individuals with smart virtual objects from a MySQL database. A pilot study with 18 children with ASD that have learning difficulties, showed significantly higher engagement and concentration time. (Teo et al., 2021) found that socio-cognitive video games within a neurofeedback therapy may train working memory, selective and sustained attention of children with ASD and co-occurring ADHD. Here, eye gaze and electroencephalogram patterns (EEG) were sensed and classified by some machine learning algorithm. The attention score is then used to control the avatar's speed in the attention training game. A pilot study with 20 participants having comorbid conditions of ASD and ADHD showed that their interest and motivation could be sustained with appropriate support. Finally, (Cañete et al., 2021) developed a prototype of a tunnel-shaped smart toy enhanced with electronic components, to improve user–product interaction by making use of visual, proprioceptive, and auditory stimuli. However, the toy has not been tested yet.

Music seems to be another way to help children with ASD. Specifically, the work of (Shahab et al., 2022) shows that a smart virtual social robot teaching music on a xylophone has positive impact on the social behavior of ($n = 12$) children with high-functioning autism. Clearly, the kind of music (instrument and rhythm) is essential for the therapy. This is an open research area at the time of writing.

To assess the physiological response of a child during game play, (DiPalma et al., 2017) presents an IoT-based platform sensing EEG signals as well as electrocardiographic activity. A pilot study on five children with ASD shows a clear correlation between dynamic changes in the behavior and the corresponding physiological signals. (Faria et al., 2020) developed an interactive game for educational therapy based on an EEG brain computer interface to assess the concentration levels of children with ASD when engaged in cognitive tasks. Preliminary results indicate that brainwaves can be successfully related to the three classes *concentrated*, *relaxed* and *neutral* by using various classical machine learning techniques.

Other papers follow a validated therapeutic protocol. The two Applied Behavior Analysis (ABA) teaching styles Discrete Trial Training (DTT) and Pivot Response Training (PRT) are widely accepted methods. The DTT approach breaks skills down to their most basic parts. Each basic step is taught step by step. Desired behaviors are rewarded. Using ICT technology, the open-source software packaged ABCD by (Artoni et al., 2013), using DTT elements, is a game based on reinforcement learning where the reward is some animated Graphics Interchange Format (GIF). To increase selective and sustained attention of children with ASD within virtual reality, the humanoid in (Yun et al., 2016) adapts its dance routines to eye gaze and emotions (by Kinect's motion device), to attract the child's attention. This robot was also designed within the therapeutic DTT framework.

To overcome repetitive behavior, the European FP7 project DREAM in (Cao et al., 2019) was concerned with the development of an autonomous social robot, operating in a feedback-loop with the child. In the forward loop, the robot picks one from a pool of 40 different tasks to engage the child. In the feedback loop, Kinect's motion sensing device for gaze estimation, skeleton joint-based action recognition, face and facial expression recognition, object tracking, and audio data processing. Gaussian mixtures based classifiers output the probability for a particular behavior. The proposed system passed a clinical test in two stages. In the first and second phases, the number of participating children with ASD were 11 and 21, respectively.

Finally, handwriting is also known to be challenging due to difficulties with fine motor skills. To address this issue (Palsbo & Hood-Szivek, 2012), developed a haptic robot to teach hand-writing skills to children who reverse letters. (Sotoodeh & Taheri-Torbati, 2021) teaches motor skills by augmenting the instructor's real silhouette with points on his joints. The result was presented on a computer monitor. For 24 students with ASD, it was easier to imitate the teacher's movements on such point-light display than without. Gaze-recording during the experiment revealed that most of the kids focused on the arm of the teacher. Finally, we want to point out the interactive application

by (Préfontaine et al., 2019), to reduce engagement in stereotype behavior such hand flipping, tearing papers and mouthing. The smartphone app teaches children to play or task materials in a manner consistent with their intended function or, for television watching, sitting on the couch, facing the television without touching the remote control. The app, in 8 out of 11 participants reduced stereotype behavior. Often children with ASD also suffer sensory processing disorders . The therapeutic approach by (Javed et al., 2020) consists of two robots, a humanoid and an iPod that visit one of seven stations (such as smelling, tasting, touching) and move to one of 20 emotions states according to Russell's circumplex model of affect. Their approach was successfully tested on five children.

To improve in-class behavior (Beaudoin et al., 2021), present a humanoid robot and a haptic bracelet, to occupy children with ASD and to learn to use their time more efficiently. Unfortunately, the pilot study includes only two participants. To tackle repetitive behavior (Tentori et al., 2015) follows an augmented reality approach. The teacher maintains an electronic behavior record of each student. Virtual hot-air balloons, each presenting one child in class, are projected on the wall. The color of the balloon depends on the respective student's behavior. Sixty children benefit from this approach over a period of 6-months.

To improve pretend-play, a smart mirror (screen) replaces the items the child is playing (e.g. a wooden block) with an imaginary alternative (a car) (Bai et al., 2015).

Moving to behavioral education in daily life (Mruzek et al., 2019), deployed a wireless disposable sensor in the child's underwear. A mobile application signaled the parents the onset of urination, time-stamped accidents for analysis and reminded parents to reinforce intervals of continence. A pilot study comprising 33 low-functioning children with ASD showed a reduction of accidents over 3 days from ca. 90% at week 2 to ca. 60% after 3 months at the end of the therapy. The interactive virtual environment created by (Almazaydeh et al., 2022) supports ($n = 9$) children with ASD to independently go to school, cross a street, or prepare for a bus trip. To make children with ASD go to the dentist (Narzisi et al., 2020), prepared the interactive web application "MyDentist." A pilot study with 59 children leads to improved oral hygiene and cooperation during dental treatments.

Finally, it is worth noting that teachers in a class settings spend a considerable amount of time in helping students stay focused on a particular task. To address this issue (Escobedo et al., 2014), developed a real object that can "feel" using IoT technology, to support teachers in training children with ASD object discrimination, and as the students are progressing, task discrimination, as well. A pilot study with 18 students indicates that smart objects reduce students' behavioral problems while improving their cognitive efficacy at the same time.

6.3.2. *Management of anxiety*

Management of anxiety is treated in the literature as independent object of intervention. For the diagnosis (Puli & Kushki, 2020), quantified physiological arousal by deploying a (linear) Kalman filter with heart-rate and accelerometry signals (the latter reduces false positives) from a commercially available IoT wearable as input signals. A clinical test on 15 children with ASD with IQ above 50 revealed 93% accuracy. The clinical test in (Nguyen et al., 2021) shows that the anxiometer, a wearable using the approach in (Puli & Kushki, 2020), indeed improves awareness of anxiety in ASD children. (Iakovidou et al., 2020), instead, deployed various (non-linear) machine learning algorithms, to jointly classify ASD and Rett syndromes. The test accuracy is similar, namely above 92%.

For the treatment, the ICT tool developed by (Kuriakose & Lahiri, 2017) uses also IoT technology to sense biomarkers related to anxiety, but the data is fed into various machine learning algorithms capable of predicting the affective state e.g., anxiety that, in turn, adapts the task in the virtual environment gradually and automatically, to counteract anxiety. The system was successfully tested on nine children with high-functioning ASD. Clearly, ICT-based treatment of anxiety is still an open research issue.

7. Monitoring vs. intervention

The second dimension of our investigation in Figure 2 is concerned with the system activity ranging from monitoring to intervention.

According to the Cambridge dictionary, *monitoring* refers to "watch and check a situation carefully for a period of time." Clinicians may monitor the individuals' diagnostic and therapeutic processes. *Intervention*, in contrast, refers to an "intentional action, to change the situation." Translating these definitions into technical terms, we need to design a control system with feedback. The forward control collects data from sensors and analyses the result, to monitor the triad of impairment. The feedback control of the loop either proposes therapeutic intervention to the clinician, or intervenes on its own in an autonomous fashion. Following either approach, the literature follows three different research threads to system interactions with individuals with ASD (cf. Tables 2–4):

- exclusive monitoring activities;
- exclusive intervention activities;
- a combination of monitoring and intervention activities.

7.1. *Monitoring only*

For periodic monitoring of the patient's psycho-physical conditions with respect to the progress of therapy, the literature reveals innovative ICT solutions for the triad of impairment. For communication, Table 2 reveals five contributions related to logopedic monitoring: a web application, to assess language skills in Taiwanese (Lin et al., 2013); a prototype of an audio augmented paper for low-functioning children with ASD that uses the children's own voices to foster attention (Alessandrini et al., 2014); an ICT tool relying on immersive virtual reality for verbal/nonverbal input interaction in children with high-functioning ASD (Halabi et al., 2017); a language development and literacy software application (Boyle & Arnedillo-Sanchez, 2022); and computer-assisted breathing exercise using IoT technology and ambient intelligence, to control stress in children with ASD (Morales et al., 2022).

Moving to social interaction, there are numerous applications that address skill development. (Wade et al., 2017) presents a collaborative game, to enhance dyadic collaboration. The real-time virtual environment presented in (H. Zhao et al., 2018), takes a similar approach. Other papers focus on social assisted robots (SARs) that teach skills using feedback information on the facial expression of the child (Saleh, 2019; Valadão et al., 2016; Wan et al., 2022). SARs have also be used to teach children with ASD turn-taking skills via music therapy (Feng et al., 2022). In combination with IoT such SARs can become autonomous agents with the capability of teaching skills while obtaining feedback from the sensor readings (Hachisu et al., 2018; Lang et al., 2021). Finally, it is worth pointing out two IoT solutions that monitor attention. (Zheng et al., 2017) focus on gaze tracking using a distributed array of cameras, while (Douglas et al., 2021) deploys IoT wearable ultrasound sensor technology, to validate social proximity (face-time and frontal proximity).

Only one work is concerned with social interaction-based ASD diagnosis (W. Zhao & Lu, 2020): feeds a neural network with facial expressions from children.

For social behavior, there are indeed a number of ICT tools for ASD diagnosis available. For restricted and repetitive behavior inference, numerous ICT solutions have been proposed so far. Focusing on predictive diagnosis, the ICT tools available in the literature follow three strategies: i) detect the evolution of spontaneous and repetitive movements of the child by means of a simple time delay neural network and a recurrent neural network using IoT sensors (Bondioli et al., 2021), Long-short-term memory (LSTM) neural networks using IoT sensors (Kojovic et al., 2021); motion tracking tools from computer vision such as the Kanade-Luca-Tomasi algorithm (Caruso et al.,

2020); or support vector machine using virtual reality (Raya et al., 2020); ii) detect face expression of the child during some induced activity such as watching a video (Egger et al., 2018); iii) test various visual search and concept classification skills during serious games (J. Chen et al., 2019). For anxiety inference, literature search revealed one app for diagnosis and another for treatment. The former is based on machine learning-based classification from physiological signals using IoT (Iakovidou et al., 2020). The latter deploys a linear Kalman filter instead (Puli & Kushki, 2020).

For the therapy of restricted and repetitive behavior (DiPalma et al., 2017; Faria et al., 2020), presents an interactive game in combination with a brain–computer interface, to assess the concentration levels. The humanoid robot and a haptic bracelet in (Beaudoin et al., 2021) teach children with ASD be more time efficient. Finally, we want to point out the work by (Johnston et al., 2019) addressing an immersive audio platform that aims at examining auditory spatial attention and sound localization ability. In all these examples, data was logged in a transparent way to users without distracting their attention during the activity they were currently carrying out.

7.2. *Intervention only*

Considering exclusively intervention activities for communications, literature revealed three ICT tools for visual languages, to compensate for deficits in functional communication and language skills in children with ASD. Following this approach, the interactive game by (Rahman et al., 2011) helps children to utter intelligible sounds for a given image on the screen; the speech therapy system by (Castellanos et al., 2022) translates images to speech for the user to pronounce; and the smartphone application by (Gevarter et al., 2022) to create multi-symbol messages.

However, there are several ICT tools for logopedic intervention available in the literature. To highlight a few intervention activities, the tablet application by (Venkatesh et al., 2012) teaches toddlers words, their relations, and utterances while that by (Macpherson et al., 2014) models and records on video verbal compliments and compliment gestures and that by (Güler & Erdem, 2022) is based on (animated) social story maps. As children with ASD often exhibit poorer speech processing and auditory processing compare to neurotypical peers, the web-based application CAPODOTS by (Schafer et al., 2019), a dichotic listening training program that uses interaural and adaptive lead – lag timing differences. Social assisted robots, instead focus on reading comprehension (Louie et al., 2020), dictations, vocabulary, articulation, and pronunciation as well as literacy skills (Egido-Garcıéa et al., 2020).

Moving to social interaction, there are a few ICT applications worth mentioning. Joint attention is an early risk marker for ASD. The SAR (Goodrich et al., 2012) assists the therapist to initiate a joint attention scenario while the SAR in (Bekele et al., 2013) operates autonomously (Nie et al., 2021). In contrast, it follows an immersive computer-mediated approach using a commercial Kinect-based body tracker. Other ICT tools help children with ASD manage their emotions. When it comes to collaborative skills development, the serious game ECHOES (Porayska-Pomsta et al., 2018) comprises a virtual agent that intervenes during the social interaction with the conversation partner. In (Modugumudi et al., 2013), children with ASD located in remote locations may interact with each other in a collaborative virtual environment. The collaborative puzzle in (Ben-Sasson et al., 2012) is a serious game to complete mutual goal. To assist children with ASD in managing emotions with the help of machine learning, the intelligent mirror in (Pavez et al., 2021) reflects the meaning of the users' own emotion they are trying to imitate. In contrast, augmented reality by Google' superpower glass uses emojis to visualize the emotion of the conversation partner during a social interaction (Daniels, Schwartz, et al., 2018). Modern (humanoid) SARs in combination with IoT involve facial expression recognition, landmark extraction, and gaze estimation, to extract gestures and provide dynamic feedback in real-time (Del Coco et al., 2018; Zheng et al., 2016). The SAR by (Nunez et al., 2018) teaches children with ASD turn-taking through play.

Let us now turn to training of social behavior. Often children with ASD show a repetitive behavior such as twirling, hand-flipping, or vocalizations also known as *stimming*. These markers, occurring for a few seconds or longer, are the entry point to modern ICT tools. Play therapy has been an importance practice since the beginning. Some papers follow an heuristic approach such as the 3D-dolphinarium (Cai et al., 2013) and the Minecraft-style virtual environment (Shapi'i et al., 2018) controlled by the motions of the child using Kinect technology; other papers use the theoretical therapeutic framework Discrete Trial Training (DTT) such as the game-based reinforcement learning by (Artoni et al., 2013) and the humanoid SAR by (Yun et al., 2016). Desired behavior is rewarded by some action like an animated Graphics Interchange Format (GIF) and a dance routine, respectively. All these games reduce engagement in stereotype behavior (Préfontaine et al., 2019). Augmented and virtual reality have been used to teach several aspects of social behavior: to improve concentration time (Amara et al., 2022; Teo et al., 2021), to make children with ASD more independent in daily life (shopping, going to school (Almazaydeh et al., 2022) and to visit a dentist without emotional breakdown (Narzisi et al., 2020). A smart virtual SAR teaching music improves the social behavior in children with ASD (Shahab et al., 2022). Other ICT tools focus on sensory-motor therapy in ASD. To highlight a few, the exergame by (Caro et al., 2017) improves hand-eye coordination, the augmented silhouette of the instructor elicits the children's sensory motor coordination, while promoting their skills, (Sotoodeh & Taheri-Torbati, 2021). To train task discrimination and hence to improve time management, (Escobedo et al., 2014) designed a smart object that can "feel" (sensors), "think" (micro-controller), and "act" (sound, light) (Tentori et al., 2015); the virtual hot-air balloons assigned to each child in the classroom adapt their color to the behavior of the individual (according to the teacher's assessment).

Anxiety is a common marker of ASD. Here (Kuriakose & Lahiri, 2017), deploys an IoT wearable sensing physiological signals related to anxiety, to initiation relaxation techniques in a virtual environment.

Finally, we want to point out that handwriting is often a challenge for ASD children due to difficulties with fine motor skills. The haptic robot in (Palsbo & Hood-Szivek, 2012) addresses this task.

7.3. *Monitoring and intervention*

Finally, there is small number of ICT tools that support monitoring *and* intervention. For example, the wearable IoT solution by (Daniels, Haber, et al., 2018) follows a data-driven approach for progress monitoring as well as personalized intervention, in real-time. Moving to robotics, the autonomous SAR by (Cao et al., 2019) performs multimodal cognitive nonverbal and verbal interactions in the feedforward loop and monitors eye contact and touch activities of the user in the feedback control loop. Finally, the IoT application by (Mruzek et al., 2019) aims to overcome incontinence in individuals with ASD. Finally, the metaverse makes people feel more included than in real life (Lee et al., 2022).

8. Conclusions

Several studies underline the positive effect of daily use of ICT applications on children with ASD, not only in learning and autonomy contexts but also in social situations. The effectiveness of ICT in teaching various skills has been studied by many authors with very interesting results and many papers have proven the advantages of using technologies like video modeling techniques, augmented reality, virtual reality and metaverse, to facilitate communication and for the development of social skills.

Most of the current surveys on this subject, however, are rather narrow as they focus only on a specific technological solution, and often address a specific aspect of ASD. In this work, instead, we aim at a broad analysis of the literature on innovative technological solutions, classified according to three distinct aspects, namely the triad of impairment (either communication, social interaction, or social behaviors), the research purpose (either diagnosis or treatment), and the system activity (either monitoring or intervention).

The survey of the literature found a number of specific issues still open to research (for example, ICT tools exploring Pivotal Response Training, treatment of anxiety, music therapy, and the metaverse); however, it also returns a rather fragmented research area over which several initiatives are conducted at many different levels and with different technologies, often experimenting with the most recent ICT developments to look for new strategies. We believe that this is a first sign of lack of maturity in this research area. A second sign that calls for a further advancement in the methodology adopted in the assessment of technologies in this field, is that, although most of the papers analyzed in the present survey implement a validation of the proposed solutions in pilots/experiments conducted with real users. Only in very few cases, the experimental protocol establishes a control group of users. A third problem we encountered is the difficulty of transferring interesting design proposals into real life. In the vast majority of cases, the life cycle of a promising project stops after tests with a few dozen users, without having a real impact in improving the quality of life of persons with ASD. A research effort is needed both in the effective involvement of persons with ASD in the participatory planning of ICT systems and in the guidelines for technology transfer toward real tools and services.

For the adopted technologies, we observe a prevalence of virtual reality/digital world approaches in those papers addressing communication impairments, while for the papers addressing social interactions or social behavior we observe a wide (and more balanced) mix of technologies, spanning from IoT to robotics, digital reality, and gamification. The growing recent interest in the metaverse is not surprising either.

As for the research objectives, alongside some established trends that have been studied for a long time and that are relatively well developed, such as robotics to enhance collaborative skills, diagnosis through detection of repetitive behaviors, and play therapy in treatment for example, we also observe very new trends. In particular, the management of anxiety has stimulated interest only recently and that could become a hot topic in the near future.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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