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Pictogram room augmented reality technology games improve body knowledge, imitation, and joint attention skills in autistic children with intellectual disability

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Body knowledge, imitation, and joint attention are foundational for child development, yet many autistic children with intellectual disability struggle to acquire these skills. This study evaluated the effects of an educational intervention using *Pictogram Room* (PR), an open-access augmented reality (AR) technology program with games targeting these abilities. Twenty-three autistic children with intellectual disability (ages 7–14) from Spain, Bulgaria, and Türkiye participated. A stepped wedge randomized design was implemented across two groups. Over 27 sessions, delivered in their usual educational settings by their regular staff, participants showed significant and sustained improvements in body knowledge, imitation, and joint attention. This is the first AR-based intervention shown to simultaneously enhance these three core skills in this population. The program is brief, socially valid, and requires no specialized training, making it a promising tool for inclusive educational practice.

Keywords Autism, Intellectual disability, Body knowledge, Imitation, Joint attention, Augmented reality technology

Autism, also known as Autism Spectrum Disorder in the current Diagnostic and Statistical Manual of Mental Disorders (DSM-5-TR)[1], is a neurodevelopmental condition characterized by persistent deficits in social communication and social interaction across multiple contexts (e.g., a failure to initiate or respond to social interactions and abnormalities in eye contact and body language), and restrictive and repetitive patterns of behavior, interests, or activities (e.g., stereotyped movements). An autism diagnosis can be accompanied by language difficulties and cognitive impairment, being rather common to have a comorbid diagnosis of autism and intellectual disability[1]. These symptoms are present in the early phases of the developmental period, indicating that a child who is later diagnosed with autism has a different early development from that of a non-autistic child[2], and this is especially the case of autistic children who also have intellectual disability. This different early development is characterized by difficulties in basic skills such as body knowledge, imitation, and joint attention that – if not fostered – can persist over time and hinder the acquisition of more complex learning that is key to an optimal development of the infant.

Body knowledge refers to the immediate and continuous knowledge that a person has about their own body in a static state or in movement, in relation to its different parts and the space and objects that surround it. This perception results mainly from the integration of multiple exteroceptive (visual, tactile, and auditory) and proprioceptive (coenesthetic and kinesthetic, especially vestibular, muscular, joint, and tendon) sensory information. Body knowledge also refers to the awareness of oneself as a mental and social entity, and to the

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feelings that this awareness offers, constituting a fundamental basis for self-identity[3]. From birth, the infant develops the perception of their body through interaction with others (e.g., through caresses) and objects. At the ecological level, body knowledge appears in non-autistic children at around four months and facilitates the development of the sense of effective agency (i.e., the experience of initiating and controlling one's actions and producing desired changes in the world through these actions[4]. At a symbolic level, self-recognition is the ability to recognize the representation of oneself as 'me'. Non-autistic children tend to reach this level in front of a mirror at around 18 months[5]. Later, around the age of three, they can recognize a self-representation that does not look like themselves (e.g., an avatar). By the age of five, they can already create a mental representation of themselves as a social person. Because we engage with the world and each other through our bodies and bodily movements, being able to represent one's own and others' bodies is fundamental to human perception, cognition, and behavior[6]. Adequate body knowledge contributes to good motor coordination, spatial cognition, body language, and emotional expression[7]. Many autistic people experience difficulties developing adequate body knowledge. Consequently, they may experience deficits at the motor level (e.g., slowness, awkwardness or lack of coordination) and at the perceptive level (e.g., lack of hand-eye coordination, spatial organization, or spatial-temporal structure) that limit them to interact and function comfortably in the environment around them[8–10].

Imitation, in its simplest form, consists of doing what someone else or something else does. In addition, imitation takes different forms, has different uses, and generates different brain activities according to each of these uses[11]. For this reason, it is important to specify when to imitate, what to imitate, and how to imitate. As for when to imitate, one can discriminate between three types: (1) *synchronic imitation*, which consists of doing the same thing at the same time; (2) *delayed imitation*, which consists of doing the same thing albeit after a short period of time; and (3) *deferred imitation*, which consists of doing the same thing yet only after a long period of time. Actions imitated can be known or new, and simple or more complex. And, as to how it is imitated, it can be done (1) exactly or roughly, (2) completely or partially, (3) from scratch or after multiple corrections, and (4) spontaneously or on request. Therefore, it is a skill that takes many forms that develop at different developmental times. Babies tend to first imitate some facial gestures and sounds (newborn), then hand gestures (2 months), subsequently other body trajectories (3 months), and finally simple actions (6 months), with grasping being the most representative in the latter category. It is around three years of age when the infant can reach the most complex level of imitation, that is, chaining many actions to perform the exact imitation of a new action in a deferred manner. Not to forget, imitation has two facets: imitate and be imitated. When coordinated, these two facets make it a genuine communicative system allowing nonverbal turn-taking, synchrony, and shared topics via doing the same action at the same time. Imitation behavior allows people to learn the typical use of certain objects, acquire new skills, and obtain the necessary bases for the development of communication. Besides, this skill is essential because it contributes to learning through observation, self-recognition, and recognition of body parts, communication without words, joint attention, empathy, relationship with others, and the development of Theory of Mind (ToM; i.e., the ability to attribute mental states, such as desires, thoughts, and intentions, to oneself and others[12]. Many autistic infants do not develop the ability to imitate at the developmental stage that would be desirable and, as a consequence, they have difficulties in this and other related areas that are essential for their development, such as play skills, interaction with peers, language development[13], or joint attention[14]. A large meta-analysis has shown that motor coordination deficit is a cardinal disability in autism, whatever the form and level of autism, the age and mental level of the person[8]. From this, and other related recent studies[15], it appears that imitation can be a difficulty that arises from deficits in motor difficulties or that the difficulties in imitating others' movements impede a good motor coordination development. Since imitation is multifaceted and multifunctional with different underlying brain mechanisms, this also explains why some forms of imitation are intact, and why motor training can improve the development of imitation[16–18].

Joint attention (JA) can be defined as the shared focus of two individuals on an object or event. JA occurs when one individual gets the attention of another towards an object or event using eye-gazing, pointing or other verbal or non-verbal indications. JA is achieved when, for instance, two individuals look at each other's eyes, one of them points to an object, both look at the object and afterward they look at each other's eyes again. It is said then that 'they have shared the experience of that object'. JA has been widely divided into initiating JA (IJA) and responding to JA (RJA)[19–22]. IJA refers to the use of eye contact, gaze shifting, and gestures to direct the attention of a social partner to a referent of interest[23,24] while RJA refers to responding by gaze following, pointing or showing to enhance social interaction with others[25–27]. Infants typically develop the ability to participate in JA interactions (e.g., coordinated eye gaze) at between six and twelve months of age[21,28,29], and they successfully gaze follow and point before 24 months of age[30,31]. JA skills are essential for social interaction and language development. Particularly, gaze following has been considered an important RJA skill, because it contributes to understanding what another is thinking, feeling, and intending to do[32–34], thereby facilitating the development of ToM[35,36].

Research has indicated that IJA and RJA are two distinct JA forms that develop differently –and are associated with different brain patterns[37]– as individuals grow older[38–40]. According to previous studies, when infants are at the preverbal stage, significant differences can be observed in the RJA and IJA skills of autistic infants compared to non-autistic infants, the first being much more affected, especially in the ability for RJA. More precisely, it has been found that autistic children do not engage in the RJA skills of following gaze, showing, and pointing as non-autistic children do[41–43]. However, that difficulty with RJA among autistic children becomes less evident as their language or mental age level exceeds what is typically observed in 30-month-old children. IJA differences between non-autistic and autistic children, instead, do not appear to begin to remit at 30 months of age but continue through the preschool period, and in some cases even through adulthood[27,44–46]. Therefore, RJA difficulties are critical to many aspects of development in autistic children, with early language development being the most prominent one[44,47], whereas IJA difficulties appear to be more associated with developmentally chronic differences[48]. Consequently, autistic children who have difficulties in JA may miss many opportunities for communication, socialization, and significant learning. Recent research using eye-tracking paradigms has shown that increased visual attention to JA cues is positively associated with cognitive and language development in autistic toddlers[49].

Body knowledge, imitation, and JA can be improved in autistic people and, for this reason, the most widely used evidence-based intervention programs for autistic children, such as the *Early Start Denver Model for young children with autism*[50], include activities that aim to improve these skills, acknowledging the interrelation in between them[51]. Also, specific intervention programs aiming at each skill separately have shown some efficacy (e.g., *Psychomotor Training Program*[52]; *Reciprocal Imitation Training*[53]; *IMET therapy*[11]; *Joint Attention*, *Symbolic Play Engagement and Regulation*[54]. However, these intervention programs frequently require costly and intensive training before one can implement them effectively. As the necessary resources are not always available, more affordable and complementary ways of pursuing and maintaining these key skills are needed.

Besides, the use of digital technologies has also become a source of training opportunities for autism, because it offers mainly visual information that can be highly predictable and customizable according to the tastes, interests, and educational and sensory needs of each person[55]. Augmented Reality (AR) is one of these technologies and it combines the information one perceives from the real world with information generated by the computer in real-time[56]. AR technology's main advantages for autistic individuals compared to other technologies are threefold. Firstly, AR can be considered a tangible presence[57] in that the moment-to-moment awareness of autistic users in the process of perceiving and acting in the world is much more natural than other technologies such as Virtual Reality where the reality is simulated. Secondly, AR includes body representation which can help autistic individuals to perceive themselves and track their movements contributing significantly to maintaining body awareness[58]. Thirdly, since AR combines both real and virtual characteristics, it can be a useful tool for scaffolding the generalization of skills learned in a virtual world to the real world[55], which is highly desirable in interventions for autistic people. This has triggered a proliferation of intervention studies using AR technologies to enhance skills in autistic people and, as a result, the number of studies systematically reviewing the impact of these interventions has also increased. Recent systematic reviews indicate that, although multiple methodological limitations were identified about the quality of the included studies, promising findings may suggest the effectiveness of AR in improving skills in autistic children[59,60], including JA[61]. One of the technologies that has been used in several studies is Pictogram Room (PR).

PR is an AR technology the first version of which was created in 2011 by researchers at the Universitat de València, in Spain, in collaboration with international autism stakeholders. It has received numerous national and international funding rounds until its current version which was launched in 2023. PR consists of a set of educational AR video games that, based on scientific findings, were specially designed to improve a wide variety of skills in autistic people, including body knowledge, imitation and JA[62,63]. PR, which is openly downloadable for free in English, Spanish, French, Bulgarian, and Turkish, has been successfully used as a tool to assess body knowledge skills in autistic people[64]. Moreover, it has been effective in improving the sensorimotor skills of five autistic boys and girls between 4 and 6 years old in a school in the United Kingdom[65] and the RJA skills of six autistic boys and girls with intellectual disability between 3 and 8 years old in a school in Spain[66]. In this latter study, a PR game called *Gaze following* was used by teachers for 6 intervention sessions to train children to follow the gaze of a digital dummy and point to the object that the dummy was looking at. According to the study results, the PR game was effective in improving these RJA abilities. However, the authors highlighted a series of limitations such as a relatively small sample and in a specific study context, the use of ad hoc non-validated RJA assessments, and the lack of a protocol to systematically evaluate the procedural fidelity of the intervention implementation. The present study built upon these limitations and aimed at exploring further the potential of the PR. To the authors' knowledge, no previous study has explored the effect of this or any other AR technology tool to improve body knowledge, imitation, and joint attention skills in the same intervention program.

Thus, the objective of this study was to evaluate effects of PR on RJA[66] as well as on IJA, body knowledge, and imitation skills of autistic children with intellectual disability. This evaluation was conducted with participants of a larger age range and from different countries, applying a systematic evaluation and implementation protocol across two experimental groups. In line with the study's objectives, the following research question was formulated: to what extent does an educational intervention using PR games improve body knowledge, imitation, IJA, and RJA in autistic children with intellectual disability? Based on prior studies and theoretical foundations, we hypothesized that an educational intervention using a selection of PR games, designed for autistic boys and girls with intellectual disability, and implemented by center staff, would result in statistically significant improvements in their body knowledge, imitation, IJA, and RJA skills.

Methods

Ethical approval statement

This research study was approved by the Ethics Committee of Research in Humans of the Ethics Commission in Experimental Research of the Universitat de València on the 12th of July 2022 with register code 2,011,042. This study also abides by The Ethical Principles for Medical Research Involving Human Subjects of the Declaration of Helsinki[67].

Informed consent statement

Prior to the study, a one-hour meeting was arranged at each participating center in which the purpose of the study and methods applied were explained by center staff to parents. Given that the participating children could not provide their own consent due to their young age and intellectual disability, one of their parents signed the consent form for each child. The consent form included permission for their participation and for capturing images and videos for research purposes, including the publication of images in an online open access publication. All participants were informed of their right to withdraw from the study at any point.

Participants

Twenty-three children, 21 males and 2 females, participated in this study. They were recruited from one special education school for autistic students in Spain (4 children), one center that offers social services to autistic individuals in Bulgaria (11 children), and one special education school with autistic students in Türkiye (8 children). Children were selected by center staff after checking they met the following inclusion criteria: (1) they had an autism diagnosis with intellectual disability (also known as Intellectual Developmental Disorder) according to the DSM-5-TR[1]; (2) they were between 6 and 14 years old; (3) they did not have gross motor or visual difficulties, or any other health condition (e.g., continuous seizures) which prevented them from using PR; and (4) they had never used the PR tool before this study. Further information on the participants' characteristics is presented in Tables 1 and 2.

To confirm the participants' clinical diagnoses, different assessment tools were used depending on what was available in each center and language. For the autism diagnosis, the Autism Diagnostic Observation Schedule, Second Edition (ADOS-2)[68], and the Autism Diagnostic Interview-Revised (ADI-R)[69] were used. The ADOS-2 is a standardized behavior observation and coding assessment tool that can be applied from 12-month-old babies to adults. There are five modules for different age and language ability ranges. The ADI-R is a standardized comprehensive interview to asses autism characteristics for children and adults with a mental age above 2 years, using 3 functional domains: language/communication, reciprocal social interaction, and restricted, repetitive, and stereotyped behaviors and interests.

Before this study started, Spanish participants already had ADOS-2 and ADI-R scores, whereas Bulgarian and Turkish participants did not have an autism diagnostic score. Therefore, licensed autism professionals administered the ADI-R to Bulgarian participants and the ADOS-2 to Turkish participants.

Participant's ID	Country	Sex	Chronological Age	Autism diagnostic tools scores					Cognitive ability tools scores				
				ADOS-2	ADI-R				Vineland-3 *Standard Scores*				Leiter- R
					C	RSI	RBI	EDD	COM	DLS	SOC	ABC	IQ
01SG2	Spain	M	14	18	11	11	3	3	40	58	36	42	
02SG2	Spain	M	12	16	10	9	3	2	63	63	56	63	
03SG1	Spain	M	13	26	12	19	6	4	34	40	34	41	
04SG1	Spain	M	8	25	11	23	4	4	20	40	26	32	
01BG1	Bulgaria	F	12		14	30	10	5					
02BG2	Bulgaria	M	10		20	14	6	4					
03BG2	Bulgaria	M	7		20	29	10	5					
04BG2	Bulgaria	M	7		14	29	6	4					
05BG1	Bulgaria	M	7		13	31	12	4					
06BG2	Bulgaria	M	7		14	27	5	4					
07BG1	Bulgaria	M	6		15	24	6	4					
08BG1	Bulgaria	M	9		22	22	7	7					
09BG2	Bulgaria	M	10		18	28	7	4					
10BG1	Bulgaria	M	8		20	26	3	4					
11BG1	Bulgaria	M	9		14	30	10	5					
01TG1	Türkiye	M	13	25									38
02TG2	Türkiye	M	11	27									–
03TG1	Türkiye	M	10	26									–
04TG2	Türkiye	M	8	25									–
05TG1	Türkiye	M	11	23									–
06TG1	Türkiye	M	13	19									40
07TG2	Türkiye	F	14	24									–
08TG2	Türkiye	M	13	28									–

Table 1. Characteristics of the 23 study participants. Participant's ID: participant's identifier, which is formed of a number given to each participant, a letter representing the country (i.e., S: Spain; B: Bulgaria; T: Türkiye), and the experimental group in which they participated (G1: Group 1; G2: Group 2); M: male; F: female; ADOS-2: Autism Diagnostic Observation Schedule, Second Edition module 1 (cut-off point = 16); ADI-R: Autism Diagnostic Interview-Revised, C: communication, RSI: reciprocal social interactions, RBI: repetitive behaviors/interests, EDD: early developmental disorders (cut-off points: 10 / 8 / 3 / 1); Vineland-3: Vineland Adaptive Behavior Scales, Third Edition, COM: communication, DLS: day living skills, SOC: socialization, ABC: adaptive behavior composite (M = 100 / SD = 15); Leiter-R: Leiter International Performance Scale, Revised, IQ: intelligent quotient (M = 100 / SD = 15).

Participant's ID	Cognitive dimensions									Intellectual Disability severity level
	Rea	PS	Plan	AT	Judg	AL	LFE	AF	TS	
01SG2	1	1	1	1	2	0	1	1	8	Severe
02SG2	0	2	1	3	2	0	2	0	10	Moderate
03SG1	1	1	0	1	1	0	1	0	5	Severe
04SG1	0	1	0	0	0	0	0	0	1	Profound
01BG1	0	1	0	0	1	0	1	0	3	Profound
02BG2	1	1	1	3	2	0	1	1	10	Moderate
03BG2	0	1	0	1	0	0	0	0	2	Profound
04BG2	0	1	0	0	0	0	1	0	2	Profound
05BG1	0	1	1	0	1	0	1	1	5	Severe
06BG2	1	2	1	1	2	0	1	1	9	Moderate
07BG1	2	2	1	2	2	0	2	1	12	Moderate
08BG1	1	1	1	2	2	0	2	1	10	Moderate
09BG2	1	1	0	1	1	0	1	0	5	Severe
10BG1	0	1	1	1	1	0	1	1	6	Severe
11BG1	0	1	0	0	0	0	1	0	2	Profound
01TG1	0	1	0	0	0	0	1	0	2	Profound
02TG2	0	1	0	0	0	0	0	0	1	Profound
03TG1	0	1	0	0	0	0	1	0	2	Profound
04TG2	0	1	0	0	1	0	1	0	3	Profound
05TG1	0	1	0	0	1	0	1	0	3	Profound
06TG1	0	1	1	0	1	0	1	0	4	Profound
07TG2	0	1	0	0	0	0	1	0	2	Profound
08TG2	0	1	0	0	0	0	0	0	1	Profound

Table 2. Assessment scores of participants' cognitive abilities. Rea: reasoning; PS: problem-solving; Plan: planning; AT: abstract thinking; Judg: judgment; AL: Academic learning; LFE: learning from experience; AF: adaptive functioning; TS: total score (0–4 profound, 4.1-8 severe, 8.1–12 moderate, 12.1–16 mild, 16.1–20 limit, 20.1–24 No ID).

Concerning the presence of intellectual disability, the Vineland Adaptive Behavior Scales, Third Edition (Vineland-3)[70], and the Leiter International Performance Scale, Revised (Leiter-R)[71] were used. The Vineland-3 is a self-report questionnaire which helps the intellectual and developmental diagnosis by the measurement of different dimensions of adaptive functioning (communication, day living skills, and socialization and motor skills), and the Leiter-R is a widely used measure of nonverbal intellectual functioning that consists of both perceptual and conceptual tasks designed to measure aspects of attention, cognition, and memory. The Vineland-3 and the Leiter-R were administered to participants in Spain and Türkiye, respectively, before the intervention study started, displaying cognitive deficits in those who completed the assessments. Most Turkish participants could not complete the Leiter-R procedure due to their difficulties being unable to get a meaningful score. Consequently, they were diagnosed with Unspecified Intellectual Disability, which is a diagnostic category assigned to individuals older than 5 years old who seem to meet the criteria for Intellectual Disability but cannot be assessed using locally available procedures (due to associated impairments including severe problem behaviors[1]. Considering these difficulties observed in the Turkish participants and the fact that there were no available tools to assess the cognitive abilities of the Bulgarian participants, A.L.-F. created an ad hoc assessment tool following the DSM-5-TR criteria for the diagnosis of intellectual disability and based on performance in the following eight dimensions: reasoning, problem-solving, planning, abstract thinking, judgment, academic learning, learning from experience, and adaptive functioning. This cognitive assessment, which can be consulted in the Supplementary Information file[a], allows for the establishment of a score for each dimension (i.e., 0–3) and a total score (i.e., 0–24) to determine the presence and level (i.e., No intellectual disability; Limit; Mild; Moderate; Severe; Profound) of intellectual disability. The center staff filled in a table with a thorough description of developmental characteristics of the participants which then was used by an independent coder to apply the cognitive assessment tool to establish the presence and level of intellectual disability to participants, which are presented in Table 2. Based on the data provided in Tables 1 and 2 and considering that participants were enrolled in governmental (either regional or municipal) education and service centers which require the presence of autism and intellectual disability, both diagnoses were confirmed for all participants.

Variables and materials

The study's independent variable was an educational intervention based on the use of five PR games. Each game includes four activities generally ordered from least to most difficult (i.e., from fewer to a greater number of stimuli, from more to a smaller number of visual supports provided, etc.).

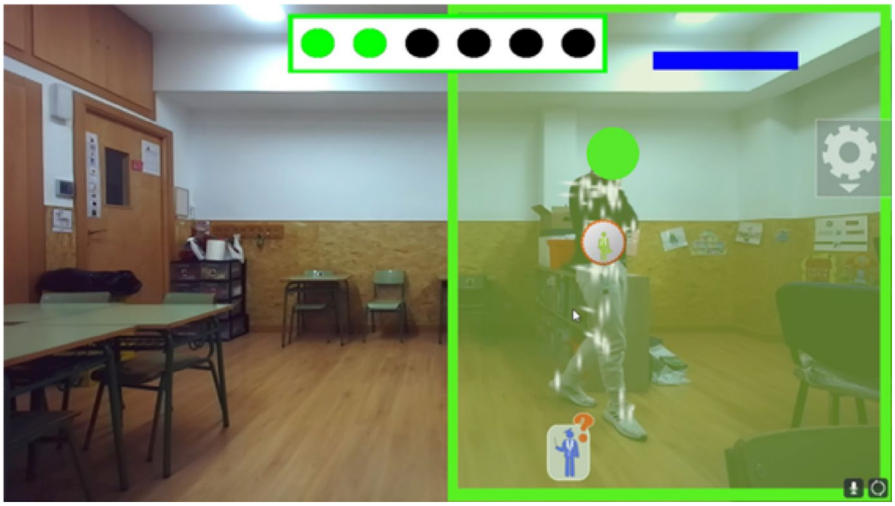

Fig. 1. An autistic child doing the PR *Moving with lights* activity of the *Movement* game. Image reproduced with permission through a consent form.

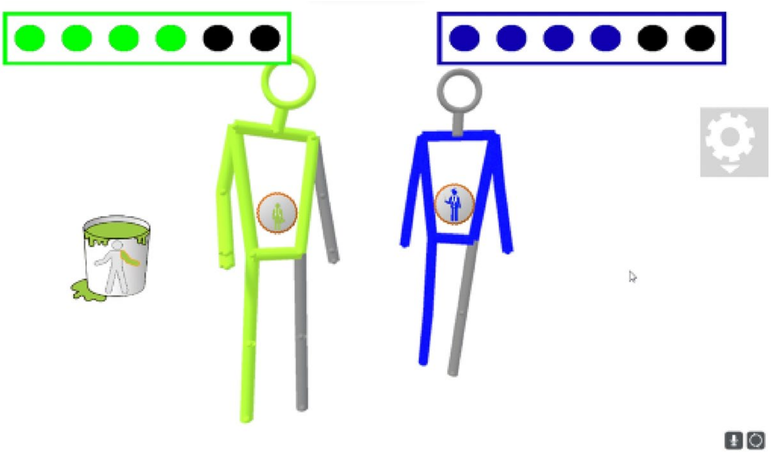

Fig. 2. An autistic participant and the teacher doing the PR *Color my doll* activity of the *Parts of my body* game. Image reproduced with permission through a consent form.

- Game 1: *Movement*. In this game, players can see their real image (as in Fig. 1) or their silhouette on the screen, board or white wall where the AR game is projected. This game includes the following four activities: (1) Movement with lights; (2) Movement with music; (3) Movement with lights or music; (4) Movement with lights and music. This game teaches the cause-effect relationship between body movement and the production of music and light effects.
- Game 2: *Parts of my body*. This game has the following four activities: (1) Color by parts, (2) Choose and color, (3) Color my doll (Fig. 2), and (4) Coloring shower. This game teaches to identify six parts of the body: the head, the right arm, the left arm, the trunk, the right leg, and the left leg.
- Game 3: *Shapes*. This game includes the following four activities: (1) Gaps, (2) Avoid (Fig. 3), (3) Hole in the wall, and (4) Jigsaw. In this game, the kid has to adapt their body posture to fit into various forms that are being presented statically or in movement.
- Game 4: *Learning to point*. This game includes the following four activities: (1) Fill the basket (Figs. 4), (2) Point with the arrow, (3) Point with the pointer, and (4) Point with the hand. In this game, the child has to collect the eggs that appear floating in the air to accumulate them in a basket and can only do so by pointing, for which they will have a different number of supports in each activity.
- Game 5: *Imitating by parts*. This game includes the following four activities: (1) Imitate arm or leg, (2) Imitate arms or legs, (3) Imitate half body (Fig. 5), and (4) Imitate the whole body. In this game, the child must imitate the posture adopted by the model (delayed imitation) that can be seen on the right side of the screen.

The PR version used in this study can be downloaded from https://osf.io/bpj3y. In this version, the PR games can be played individually or collaboratively. Games 2 and 4 accept only one player, Game 5 needs two players and

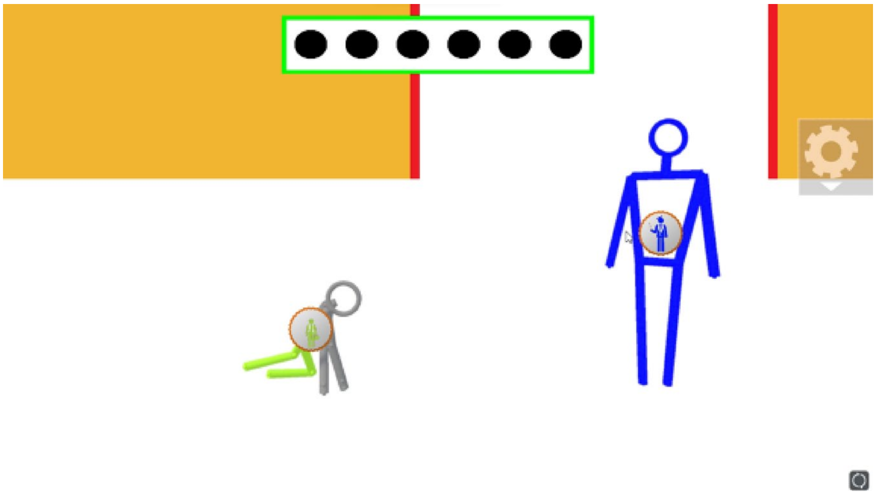

Fig. 3. An autistic child and the teacher doing the PR *Avoid* activity of the *Shapes* game. Image reproduced with permission through a consent form.

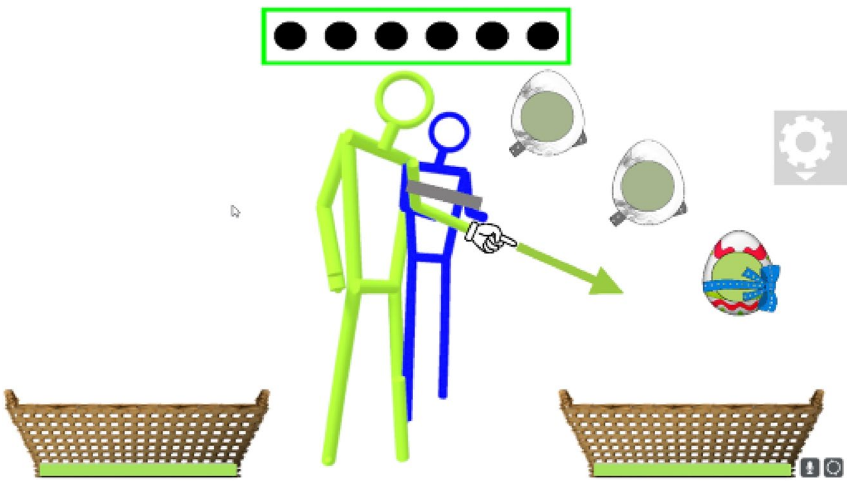

Fig. 4. An autistic child and the teacher doing the PR *Fill the basket* activity of the *Learning to point* game. Image reproduced with permission through a consent form.

Games 1 and 3 can be used by either one or two players. Each activity starts by asking the player to stay still in a natural posture for a couple of seconds in front of a virtual door at a specific distance from the screen to allow the sensor calibrate their body. If there are two players, two virtual doors are displayed, one for each. The player should keep that initial distance so the sensor can adequately track them and ensure accurate performance during playtime. The length of each activity depends on the number of goals the player has to achieve—this is indicated, as shown in Figs. 1, 2, 3, 4 and 5, with black circles on the top of the screen which become green when a goal is achieved—and the time it takes to achieve these goals. Once the player completes an activity, a reward (i.e., an icon of a hand with the thumb up) is displayed on the screen indicating to the child that the activity is over.

The study's independent variable, apart from the software described previously (i.e., the five PR games), requires the following hardware materials: a Personal Computer with Windows Operating System and an NVIDIA graphics card, a ZED 2i sensor, and a big monitor to project the games (a projector that projects the image on a white digital board or a white wall could also be used). The ZED 2i is a recently available powerful stereo camera designed for depth perception, body motion tracking, and artificial intelligence applications, and it can be deployed in a wide range of environments to provide an immersive experience. ZED 2i clearly improves the performance of its predecessors (i.e., Microsoft Kinect, Intel RealSense) in terms of field of view, resolution and general functioning. ZED 2i is not a standalone device and, to function properly, the sensor requires specific hardware, including a computer equipped with an NVIDIA graphics card and a USB (Universal Serial Bus) 3.0 port. The ZED 2i comes with a comprehensive Software Development Kit (SDK), which provides a library of functions that developers can use to integrate the sensor into their applications. Depending on the SDK version,

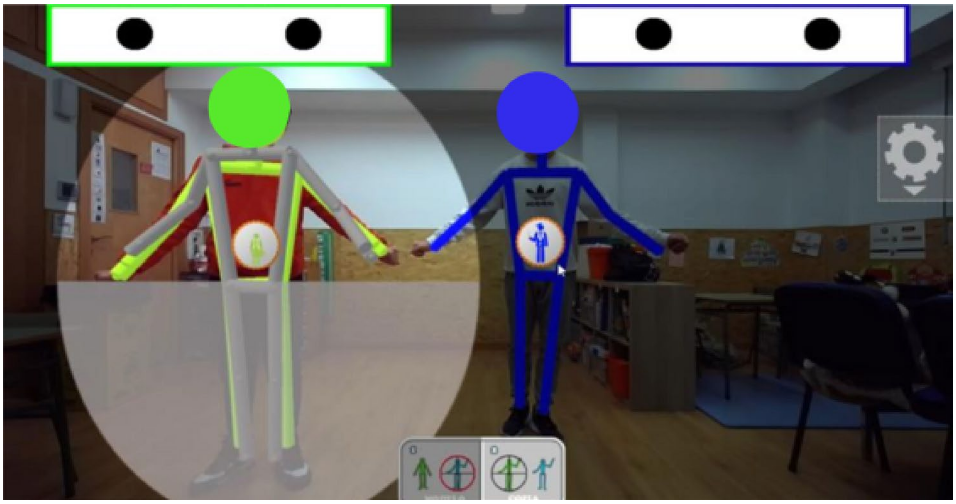

Fig. 5. An autistic child and a teacher doing the PR *Imitate half body* activity of the *Imitating by parts* game. Image reproduced with permission through a consent form.

the operating system, and the development platform used (in our case, Unity), additional multimedia libraries such as DirectX (as in the case of PR, developed for Windows) or OpenGL (more commonly used in Linux-based systems) may also be required. PR needs access to advanced features of the ZED SDK to offer sustained and optimal performance and this requires proper hardware which can be consulted here: https://osf.io/akvde.

To test the hypothesis of this study, four dependent variables, corresponding to each of the target skills, were measured: (1) imitation (IMET); (2) body knowledge (SELF); (3) IJA; and (4) RJA. This involved the collection of observable behavioral information with three instruments that are briefly described in the following. The instruments' full description, with images that help to visualize its components, and the scoring sheets used in the study can be consulted in the Supplementary Information file, as indicated at the end of each of the following.

Body knowledge (SELF)

- L.V. and J.N. created an ad hoc tool named SELF to evaluate this variable. With the use of a movement sensor, this tool creates three scenarios that show the autistic child their reflection on a white screen or a wall. These scenarios, which are ordered from most to least complex, are as follows: (1) they see their silhouette with a random color; (2) they see their silhouette with the same colors as the clothes they are wearing; and (3) they see their real image. Each scenario has a list of 6 items that represent response actions with their body, obtaining a score ranging from 0 (min) to 6 (max) in each scenario. The number of actions carried out was coded in each of the three scenarios as "0", "1" or "2 or more", understanding "2 or more" as the criterion that establishes that the child adequately recognized themselves in that particular scenario. The software created can be downloaded for free from https://osf.io/srjpu. The assessment tool description and the SELF scoring sheet used in the study can be consulted in the Supplementary Information file[b, c].

Imitation (IMET)

- To measure this variable, we used a shorter version of the evaluation tool called IMET which was developed by Nadel[11] and validated by the High French Health Authority[72]. This short version includes three subscales to assess (1) spontaneous imitation, (2) instructed imitation, and (3) recognition of being imitated. Each sub-scale comprises 6 items that, depending on the child's imitation response, can be assessed with scores from 0 to 3 (0: no interest; 1: interest; 2: partial performance; 3: successful performance), resulting in a maximum total score of 18 on each subscale. The assessment tool description and the IMET scoring sheet used in the study can be consulted in the Supplementary Information file[d, e].

Joint attention (IJA and RJA)

- To measure this construct, we used the JA Protocol[73], which has good psychometric properties[74]. This assessment tool includes two subscales, one to measure IJA skills and one to measure RJA skills. Each subscale comprises 8 scenarios that correspond to dichotomous items that are each scored with 0 (if they do not perform the action) or 1 (if they perform the action), so that, in each subscale, the participant is awarded a score between 0 and 8. The assessment tool description is openly available[73] and the JA protocol scoring sheet used in the study can be consulted in the Supplementary Information file[f].

For the administration of SELF, the same hardware needed for PR was used. For the administration of IMET and the JA Protocol only two tables and two chairs and a series of simple materials such as cups, spoons, balls or laminated posters were needed. The full list of materials required for the evaluation of the independent and dependent variables, which also included video cameras to record the study sessions, can be consulted in the Supplementary Information file[g].

In this study, Reichow et al.'s evaluative method for evaluating and determining evidence-based practices in autism[75] was used as a framework, and its research quality indicators were followed to create a strong research report. According to this method, social validity is relevant and we evaluated how important our dependent and independent variables were for the participants with two questionnaires, one for families and one for center staff, in which they had to respond to six questions with a scale from 0 to 4 where 0 was "I strongly disagree" and 4 was "I strongly agree". These social validity questionnaires, which were filled in by the participants families and center staff members before the start of the study, can be consulted in the Supplementary Information file[h, i].

Also based on this evaluative method and following recommendations for behavioral research[76], a procedural fidelity protocol was created to ensure that each study session was conducted as intended and according to the research plan. This protocol was specially designed to support the reliability and validity of the data collected across centers. In this protocol, the center staff indicated the date and the session code, which assessment was administered or which game was played in the session and had a checklist of actions required such as testing that the PR software worked or the video camera was recording properly. This protocol can be consulted in the Supplementary Information file[j].

Procedures

Study preparations

This study took place between 2022 and 2023. With the funding of the study project (ARBIT, https://arbit.adaptalab.org), the three participating centers received all the required study materials and a 3-day training course took place in Valencia, Spain, in May 2022 in which the study scientific members trained the center staff members who were going to implement all of the study sessions. They were six professionals (1 from Spain, 3 from Bulgaria and 2 from Türkiye) with different backgrounds (special education teachers, speech-language pathologists and psychologists, all with an MSc and two of them pursuing a PhD) whose specialty is autism education and have experience using digital technologies. These professionals knew very well the strengths, preferences, difficulties, and needs of the participating children before this study. Their scientific background, professional expertise, and familiarity with the participants positioned them as the most suitable candidates to implement the study sessions within the centers. The training aimed at teaching them how to: (a) administer the 3 assessment tools (SELF, IMET, and the JA Protocol including IJA and RJA) to the participant children; (b) fill in the procedural fidelity protocol; (c) use the PR and all the associated hardware; and (d) organize the meeting with families to get the informed consent for the participation of the children.

Rules applied by the professionals who intervened and evaluated the participant children

To ensure the rigor of the research study, specific instructions were followed by the professionals to intervene and evaluate the participant children. Concerning the intervention, they gave the children all the verbal and physical support they needed during the games controlling not to give more than was necessary to promote autonomy as much as possible. The games had to be played respecting an order: first, Game 1 (to be used in three sessions) and then, Game 2, Game 3, Game 4 and Game 5 (to be used in six sessions each). As each game had four activities, the child first needed to play the first activity and only when they completed it, regardless of the support provided, they could play the second activity and so on until completing the four activities. Two playing principles were established: (1) the child should play the four activities of each game as many times as possible, so they could play the four of them for many times in just one session; and (2) the child's learning pace should be respected, so if they did not complete an activity they had to stay in that activity; only in cases in which a given activity was not completed towards the end of the week in which that game was being played, they played all the activities before moving on to the next game. For the games that could be played by one or two players, they started with one player, and only when the child could play the game without any support, they could play both collaboratively. With regard to the evaluation sessions, they strictly followed the assessment instructions and they did not give any verbal or non-verbal direct support or hint to help the children to get the right answer. Verbal rewarding cues which could reinforce the right responses (e.g., very good!, well done!) were avoided and replaced by sentences generally used in natural playing contexts that do not trigger any specific response (e.g., "how many things we have here!", "let's play!"). All these rules can be consulted in the Supplementary Information file[k]. Any deviations from the established rules that could potentially bias data collection were to be documented by the professionals in the procedural fidelity protocol corresponding to the specific session.

Setting, transitioning, and adaptations

All of the evaluation and intervention study sessions took place in a room located in the school or center the participant children attended from Monday to Friday. The room was spacious enough to interact with the PR games, it had tables and chairs to administer the assessments and good light conditions (i.e., natural light that could be controlled with blinds). Children transitioned from and to the PR study room with center staff using the visual supports they normally use: laminated cards with images of the people they are transitioning with and the places where they are going or real objects that had been previously associated with the PR study room for children with low abstraction skills. When needed, the game zone was defined by applying color tape on the floor. Also, for children with auditory sensitivity, the volume of the games was kept low. The children who used either paper-based or digital augmentative and alternative communication systems (e.g., the Picture Exchange Communication System [PECS][77], could use them before, during, and after the study sessions to communicate and follow their daily routines and activities.

Experimental design

A stepped wedge randomized design[78,79] (SWT) was used. This design allows for the evaluation of differences between groups as a result of a different starting point of an intervention. Two groups were created using stratified random sampling based on center, such that in each center half (in the case of an equal number of children) or approximately half (in the case of an unequal number of children) of the participants started the intervention early and the remaining participants started the intervention a week later. There were six measurements per participant divided over four phases (see Fig. 6):

- *Baseline phase*: measurement occasions 1–2 in Group 1 (i.e., early intervention start) and measurement occasions 1–3 in Group 2 (i.e., late intervention start). This phase was included in the design to acquire a few measurements of the participants' target skills before the intervention with the PR. Both groups entered the baseline at the same time. Group 1 had two baseline weeks with one evaluation session per week (i.e., two evaluation sessions for each participant), whereas Group 2 had three baseline weeks with one evaluation session per week (hence, three evaluation sessions for each participant). Each evaluation session consisted of a 60-minute one-to-one session in which the center staff member administered the SELF, IMET, and the JA Protocol (IJA and RJA) assessments to the participant.
- *Practice phase*: measurement occasion 3 in Group 1 and measurement occasion 4 in Group 2. This phase was included in the design to have the participants learn how to play PR. In this phase, the participants played Game 1, *Movement*. This is an easy-to-play game that was selected to train self-recognition on the screen by producing music and/or light effects as a result of the participants' movements. However, as it was the first PR game used by participants, we expected that participants would focus on learning the PR functioning requirements (e.g., looking at the screen placed in front of them, controlling their position in the physical world, keeping the right distance from the screen to be adequately tracked, …) than learning what the game

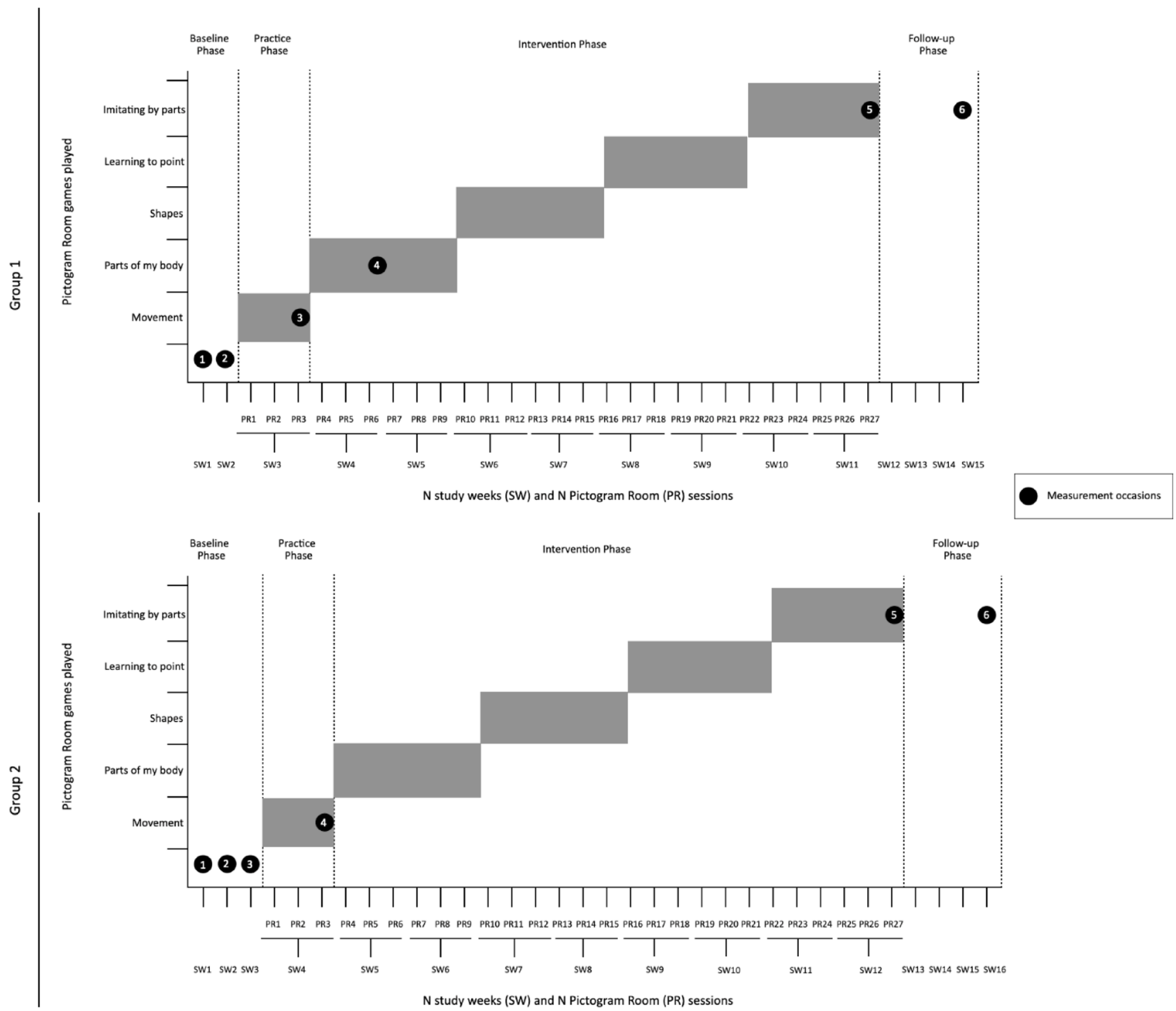

Fig. 6. Experimental design timeline for each group.

was intended to teach (i.e., body recognition). Having this first game in a separate study phase allowed us to evaluate if there was an effect on the target skills, especially on body knowledge, after the first few sessions or if, on the contrary, and as expected, no improvement could be observed after the use of this very first game. Each participant had three practice sessions of between 15 and 20 min each playing this game. After the third practice session, participants had an evaluation as described in the baseline phase.

- *Intervention phase*: measurement occasions 4–5 in Group 1 and measurement occasion 5 in Group 2. In this phase, the participants played Games 2–5, which were selected to improve the target skills. Games 2 (*Parts of my body*) and 3 (*Shapes*) trained body knowledge, Game 4 (*Learning to point*) trained joint attention, and Game 5 (*Imitating by parts*) trained imitation skills. Each participant had 24 intervention sessions of between 15 and 20 min each while playing these games. In this phase, participants in Group 1 had an evaluation session after playing Game 2 (*Parts of my body*), and participants in both groups had an evaluation session at the end of all games.
- *Follow-up phase*: measurement occasion 6 in both groups. This phase was included in the design to evaluate the maintenance of skills improvements. Four weeks after the intervention phase was completed, each participant had another evaluation session as described in the baseline phase. During these four weeks, the participant children did not play any PR game.

Thus, each participant had 27 sessions playing with the PR. Throughout the four study phases, six evaluation sessions (measurement occasions) were conducted with each participant administering each time the three assessments described above: SELF, IMET and JA (for both IJA and RJA). Evaluation 1 and 2 were done when Group 1 and Group 2 were in the baseline phase, Evaluation 3 was done when Group 1 was in the practice phase and Group 2 was still in the baseline phase, Evaluation 4 was done when Group 1 was in the intervention phase and Group 2 was in the practice phase, Evaluation 5 was done when Group 1 and Group 2 had completed the intervention phase, and Evaluation 6 was done one month after the intervention phase was completed. All in all, the study lasted 4 months (15 weeks for Group 1 and 16 weeks for Group 2).

Data collection and statistical analysis

The social validity questionnaire was created using Google Forms. Copies were first printed and then filled in by family and center staff members before the study started. The center staff members scanned the questionnaires and shared the files, with the scientific members for analysis. P.P.-F. created a database with the questionnaires' responses and the data was descriptively analyzed using the *jamovi* version 2.5.6[80].

Data generated with the administration of the SELF, IMET and JA Protocol assessments was collected through the scoring sheets mentioned previously. Scoring sheets were printed and while each professional assessed the child, scores were given to their performance in real time. The paper-based scoring sheets were digitally scanned and shared with the scientific members for analysis. P.P.-F. created a database with the scoring sheets data from the three centers and A.L.-F. randomly selected 10% of this data and checked it for accuracy.

The data was analyzed by J.L. using the *GAMLj3* package version 3.3.3[81] in *jamovi* version 2.5.6[80], using the linear mixed model for each of the four outcome variables – SELF, IMET, IJA, and RJA – treating the participant-level intercept as random effect and allowing correlations across pairs of measurement occasions to vary (i.e., unstructured residual correlation matrix) and using the Satterthwaite methods for the degrees of freedom. For each outcome variable, two different models were run, using the same random effects structure as mentioned previously, to estimate and test the fixed effects from different perspectives.

In the first model (i.e., Model 1) for each outcome variable, the fixed effects included *Center* (factor coding: deviation), *Practice phase* (dummy), *Intervention phase* (dummy), *Follow up* (dummy), *Center*-by-*Practice phase*, *Center*-by-*Intervention phase*, *Center*-by-*Follow up*, as well as *Group*-by-*Practice phase*, *Group*-by-*Intervention phase*, and *Group*-by-*Follow up*. In this model, the center (or school) effects were included to account for differences between centers in participant characteristics that may have affected the outcome variables to some extent. In addition, the rationale behind this specific combination of group effects (with *Group* being dummy coded) is that at baseline any differences between group are entirely due to randomization and not due to different treatments[79]. This model enables testing for differences between earlier and later start of practice and/or intervention (i.e., Group 1 vs. Group 2) while accounting for both phase and center differences.

Next, a second model (i.e., Model 2) for each outcome variable was a 3 (*Center*) by 2 (*Group*) by 4 (*Phase*) three-way model with the main effects of *Center* (factor coding: deviation), *Group* (dummy coding), and *Phase* (factor coding: repeated) and their two-way and three-way interactions. This model helps to estimate differences between phases and, if needed, compare trajectories across phases for different centers and for the two intervention groups (i.e., Group 1: early start, Group 2: later start).

As the interest in this study lies in fixed effects, Maximum Likelihood estimation was used for both models.

While the first model helps to examine whether in the early start group (Group 1) significant performance improvements on any of the outcome variables were observed earlier than in the late start group (Group 2), the second model provided a more direct test of phase differences. Given that the practice round only consisted of a game to become familiar with PR with only three sessions in which participants were expected to mostly focus on the functioning of the AR tool, no statistically significant difference between the *Baseline* and *Practice phase* was anticipated. However, the hypothesis used in this study dictates an improvement after (starting) the intervention, hence we expected significantly better performance in the *Intervention phase* compared to the *Practice phase*. Finally, given no further practice after the *Intervention phase*, we expected no significant improvements in the *Follow up* relative to the *Intervention phase* but included this phase to examine a possible regression towards the kind of performance observed prior to the intervention phase.

All of the study sessions were recorded. Video recordings were not used as a primary information resource but as secondary in case a center staff member was unsure about a score given to a child during an assessment or the scientific members needed to check any data inconsistencies. These recordings were also available to cross-check professionals' assessments if needed, thereby supporting the rigor and reliability of the data collection process.

Results

All participant families and center staff responded to the social validity questionnaire. Most families agreed or strongly agreed that body knowledge (17.4% agreed; 73.9% strongly agreed), imitation (8.7% agreed; 82.6 strongly agreed), and JA (8.7% agreed; 87% strongly agreed) were important skills for their children's development and learning. Most families agreed or strongly agreed that a personalized educational intervention implemented by the center staff who know their children best (34.8% agreed; 60.9% strongly agreed) and mediated by the PR AR technology (34.8% agreed; 60.9% strongly agreed) could help their children to improve these skills. Most families found the duration and intensity of the intervention adequate considering the importance of the target skills and their children's availability (30.4% agreed; 47.8% strongly agreed). No family member disagreed with any of the sentences rated. One parent's questionnaire responses were excluded from the analysis due to concerns about their validity and reliability. At the time of data collection, the parent was undergoing a highly distressing legal process concerning the potential loss of custody of their children—a process that ultimately resulted in custody being withdrawn by Social Services after the study had concluded. Although the parent did not request the child's withdrawal from the study, they completed the questionnaire in a systematically uncooperative manner—for example, marking strong disagreement with all items, in ways inconsistent with the child's developmental profile and school practices. This lack of engagement with the research process, combined with the broader context, led to the exclusion of the data on methodological and ethical grounds. Concerning the center staff responses to the questionnaire, most professionals strongly agreed (83.3%) that body knowledge was important, and all agreed (16.7%) or strongly agreed (83.3%) that imitation and JA were important skills for their student's development and learning, and that these skills could be improved with a personalized educational intervention implemented by them. All center staff members also agreed (33.3%) or strongly agreed (66.7%) that the PR AR technology could help their students develop the target skills with an intervention the duration and intensity of which they considered adequate. No staff member disagreed or strongly disagreed with any of the sentences rated in the questionnaire.

Table 3 presents key descriptive statistics per outcome variable (SELF, IMET, IJA, RJA) per measurement occasion (round: 1–6), and center (Spain: ES; Bulgaria; BG; Türkiye: TR).

Table 4 presents the fixed effects omnibus test outcomes for each outcome variable using Model 1. Given the coding specified in the 'Data collection and analysis' section, the 'center' term represents the main effect of center, 'PR', 'INT', and 'FU' are about the performance in the practice phase (PR), intervention (INT), and follow-up (FU) phase relative to the baseline, the product terms involving 'center' are about the extent to which the three centers can be distinguished in terms of the aforementioned phase differences, and the product terms involving 'ES' represent differences in phase differences as a function of whether the intervention started earlier (ES) or later.

In short, the only *Group*-related effect that is statistically significant at the 5% level is that of *Group*-by-*Intervention* and that goes in the opposite direction of what one would expect.

Table 5 presents the fixed effects omnibus test outcomes for each outcome variable using Model 2. Given the coding specified in the 'Data collection and analysis' section, in this second model, the product terms refer to center differences, group differences (early vs. late intervention start), or both (center *by* ES *by* phase) in phase differences.

Figure 7 presents the *Center*-by-*Phase* fixed effects plots.

Although we included *Center* to account for differences between centers, the numbers per center were too small to meaningfully interpret interaction effects (e.g., only 4 participants in the Spanish center), and therefore we focused on the interpretation of the *Phase* main effect which given almost no missing data and generally ordinal interactions can still be interpreted in a valid way in the face of the interactions.

Doing so, for SELF, we found a statistically significant improvement from *Practice* to *Intervention* ($B = 1.272$, $SE = 0.495$, $p = 0.012$) but no significant differences between *Baseline* and *Practice* ($B = 0.001$, $SE = 0.327$, $p = 0.997$) or between *Intervention* and *Follow up* ($B = -0.067$, $SE = 0.309$, $p = 0.827$).

For IMET, the findings are very similar: a statistically significant improvement from *Practice* to *Intervention* ($B = 7.028$, $SE = 2.562$, $p = 0.007$) but no significant differences between *Baseline* and *Practice* ($B = 0.896$, $SE = 1.910$, $p = 0.640$) or between *Intervention* and *Follow up* ($B = 1.808$, $SE = 1.661$, $p = 0.279$).

Likewise, for IJA, we found a statistically significant improvement from *Practice* to *Intervention* ($B = 1.341$, $SE = 0.430$, $p = 0.002$) but no significant differences between *Baseline* and *Practice* ($B = -0.308$, $SE = 0.373$, $p = 0.410$) or between *Intervention* and *Follow up* ($B = -0.481$, $SE = 0.371$, $p = 0.199$).

However, for RJA, we found a statistically significant improvement from *Intervention* to *Follow up* ($B = 0.906$, $SE = 0.424$, $p = 0.035$) and no significant differences between *Baseline* and *Practice* ($B = 0.713$, $SE = 0.467$, $p = 0.130$) or between *Practice* and *Intervention* ($B = 0.025$, $SE = 0.437$, $p = 0.954$).

In sum, our findings for SELF, IMET, and IJA were as hypothesized, whereas for RJA effects were observed at a later stage than expected.

Discussion

In this study, we hypothesized that an educational intervention based on the use of a selection of PR games would help autistic children with intellectual disability to improve their body knowledge, imitation, IJA, and RJA skills. To test our hypothesis, 23 autistic children with intellectual disability from Spain, Bulgaria and Türkiye of between 7 and 14 years old used the selected PR games for 27 sessions of 15–20 min with the support of

Variable	Round	Center	*N*	Missing	Mean	Median	SD	Minimum	Maximum
SELF	1	ES	4	0	2.75	3.5	1.893	0	4
		BG	11	0	3.091	3	2.427	0	6
		TR	8	0	1.625	1.5	1.768	0	4
	2	ES	4	0	2.75	3	2.062	0	5
		BG	11	0	2.727	2	2.284	0	6
		TR	8	0	0.875	1	0.991	0	3
	3	ES	4	0	2.25	2	0.5	2	3
		BG	11	0	2.909	3	2.166	0	6
		TR	8	0	1.25	1	1.389	0	4
	4	ES	4	0	3	3	0.816	2	4
		BG	11	0	2.909	2	2.468	0	6
		TR	8	0	1	0	1.604	0	4
	5	ES	4	0	5.5	5.5	0.577	5	6
		BG	11	0	3.727	4	2.24	0	6
		TR	8	0	0.75	0	1.389	0	3
	6	ES	4	0	4.25	5	2.363	1	6
		BG	11	0	3.455	4	2.382	0	6
		TR	8	0	2.375	2	2.2	0	6
IMET	1	ES	4	0	27.5	31	13.796	9	39
		BG	11	0	28.182	30	13.159	6	50
		TR	8	0	13	12	4.536	8	23
	2	ES	4	0	27.25	33.5	15.777	4	38
		BG	11	0	28.364	28	12.323	6	43
		TR	8	0	14.75	14	2.605	12	18
	3	ES	4	0	33.75	39	16.54	11	46
		BG	11	0	30	26	13	7	51
		TR	8	0	15.375	15	3.114	11	20
	4	ES	4	0	40.75	44.5	9.979	26	48
		BG	11	0	30.091	28	13.924	9	48
		TR	8	0	12.5	15.5	6.188	1	18
	5	ES	4	0	36	40	15.427	15	49
		BG	11	0	34.636	33	13.314	13	53
		TR	8	0	21.625	22	5.579	13	30
	6	ES	4	0	40.25	42.5	8.057	29	47
		BG	11	0	36.455	40	10.558	18	53
		TR	8	0	20.5	20.5	6.211	10	30
IJA	1	ES	4	0	4.5	5	1.732	2	6
		BG	11	0	3.091	3	2.343	0	7
		TR	8	0	3.5	3.5	1.604	1	6
	2	ES	4	0	4	4	1.826	2	6
		BG	11	0	3.545	5	2.544	0	7
		TR	8	0	4.25	4	1.165	2	6
	3	ES	4	0	5	5.5	1.414	3	6
		BG	11	0	3.091	3	2.023	0	7
		TR	8	0	3.75	4	1.669	1	6
	4	ES	4	0	4.75	4.5	0.957	4	6
		BG	11	0	3.182	3	2.601	0	7
		TR	7	1	3.571	4	1.272	2	5
	5	ES	4	0	5.25	5.5	0.957	4	6
		BG	11	0	3.727	3	2.054	1	7
		TR	7	1	4.571	4	1.813	2	7
	6	ES	4	0	5.25	5	0.5	5	6
		BG	11	0	3.636	3	2.014	1	6
		TR	8	0	4.25	4	1.165	3	7

Continued

Variable	Round	Center	*N*	Missing	Mean	Median	SD	Minimum	Maximum
RJA	1	ES	4	0	5.5	6	2.646	2	8
		BG	11	0	6.636	7	1.286	4	8
		TR	8	0	4.875	5.5	2.232	2	7
	2	ES	4	0	5.25	6.5	2.872	1	7
		BG	11	0	6.727	7	1.009	5	8
		TR	8	0	5	5.5	2	1	7
	3	ES	4	0	6.5	6.5	0.577	6	7
		BG	11	0	7.091	7	0.831	6	8
		TR	8	0	3.625	2.5	2.56	1	8
	4	ES	4	0	7	7	0.816	6	8
		BG	11	0	7.182	8	0.982	6	8
		TR	7	1	4.714	6	2.928	0	7
	5	ES	4	0	5.25	6	2.986	1	8
		BG	11	0	7.455	8	0.82	6	8
		TR	7	1	5.429	6	2.573	1	8
	6	ES	4	0	7.5	8	1	6	8
		BG	11	0	7.727	8	0.647	6	8
		TR	8	0	5.5	6	2.449	1	8

Table 3. Descriptive statistics per outcome variable (SELF, IMET, IJA, RJA), per measurement occasion (round: 1–6), and per group (Group 1: early start, group 2: late start): sample size (*N*), missing data, mean, median, standard deviation, minimum, and maximum.

the professionals who usually teach them in the centers they attend respectively. Participants' imitation, body knowledge, IJA, and RJA skills were assessed in six occasions throughout the study to evaluate differences between them (i.e., Group 1 early intervention start vs. Group 2 late intervention start), and across phases (i.e., baseline, practice, intervention, and follow up). The expected outcome was that participants would improve in imitation, body knowledge, IJA, and RJA as a result of the intervention with the PR games (i.e., intervention), and that these improvements would be maintained over time (i.e., follow-up). However, no improvement was expected between the baseline and the practice phases, as the PR game played in the practice phase (Game 1: *Movement*) was used to get participants familiarized with the PR tool. The findings were mostly in line with the hypothesis and they are discussed in the following paragraphs.

Determining a stable baseline in autistic participants with intellectual disability is necessary given the response variability they can have due to their continuously changing mood and associated behavioral problems. A baseline with no trend was successfully established (with two data points for Group 1 and three data points for Group 2) to allow for comparisons with later phases. Baseline data did not reveal any significant change in the practice phase, in which participants used Game 1 (*Movement*). This game offered a great chance for participants to experience the PR environment by learning the cause-effect relationship between their body movements and the production of music and light effects. This practice phase could have had an initial impact on the target skills, especially body knowledge. However, and as it was expected, no significant effects were found. This finding indicates that participants needed some time to familiarize themselves with the AR environment before they could benefit from it. Therefore, several PR sessions were needed before improvements could be observed, and the mere exposure to the AR program did not appear to affect the target skills per se.

Only after the intervention in which they used the PR Games 2–5, significant differences were identified for body knowledge, imitation, and IJA skills. Concerning body knowledge and imitation skills, the improvements constitute a positive finding, as expected from the literature indicating that these skills can be improved with educational interventions[11,50,52]. AR games have been previously found effective among autistic people[59,60], and the PR games used directly trained these deficient skills. However, the improvements observed in IJA skills are more surprising, as the difficulties in this ability have been traditionally associated with developmentally chronic differences between autistic and non-autistic individuals. This long-term belief has made other autism interventions[50,54] and previous studies with the PR[66] prominently focus on the improvement of RJA instead of IJA skills. If there is a tendency to train autistic children more in RJA than in IJA skills due to, at least partially, a higher chance of success, this, in turn, may explain why participants did not improve in RJA after the intervention with the PR. Throughout their childhood, participants may have been trained with other interventions causing a ceiling effect for RJA skills. This is supported by data, as participants' RJA scores were higher than IJA scores in the JA Protocol assessment from the beginning of the study, leaving less room for improvement.

In addition, the findings demonstrated that the improvements in body knowledge, imitation, and IJA were maintained for at least four weeks after the intervention was over. In other words, when participants ceased PR activity, the improvements remained intact, which is a very positive finding considering the difficulties autistic people with intellectual disability have to meaningfully maintain learning outcomes[82]. Besides, one of the most surprising findings is that, although RJA did not significantly improve after the intervention, it did in the follow-up phase. This indicates that there was still some room for improvement albeit in a delayed way. Ending PR

Term	F	df	df (res)	*p*
SELF				
center	2.37	2	20	0.119
PR	0.021	1	102	0.885
INT	7.719	1	102	0.007
FU	5.483	1	102	0.021
center ∗ PR	2.041	2	102	0.135
center ∗ INT	8.806	2	102	< 0.001
center ∗ FU	1.065	2	102	0.348
PR ∗ ES	0.661	2	102	0.519
INT ∗ ES	2.377	1	102	0.126
FU ∗ ES	0.008	1	102	0.927
Term	**F**	**df**	**df (res)**	***p***
IMET				
Center	8.484	2	20	0.002
PR	0.054	1	102	0.817
INT	19.236	1	102	< 0.001
FU	46.898	1	102	< 0.001
Center ∗ PR	2.607	2	102	0.079
Center ∗ INT	1.745	2	102	0.18
Center ∗ FU	3.149	2	102	0.047
PR ∗ ES	0.388	2	102	0.679
INT ∗ ES	0.015	1	102	0.904
FU ∗ ES	0.182	1	102	0.671
Term	**F**	**df**	**df (res)**	***p***
IJA				
Center	0.61	2	20	0.553
PR	0.023	1	100	0.88
INT	14.297	1	100	< 0.001
FU	2.579	1	100	0.111
center ∗ PR	3.155	2	100	0.047
center ∗ INT	0.807	2	100	0.449
center ∗ FU	0.747	2	100	0.476
PR ∗ ES	2.781	2	100	0.067
INT ∗ ES	2.63	1	100	0.108
FU ∗ ES	0.079	1	100	0.779
Term	**F**	**df**	**df (res)**	***p***
RJA				
Center	6.459	2	20	0.007
PR	3.21	1	100	0.076
INT	6.802	1	100	0.011
FU	10.921	1	100	0.001
center ∗ PR	3.472	2	100	0.035
center ∗ INT	0.566	2	100	0.57
center ∗ FU	0.723	2	100	0.488

Table 4. Fixed effects omnibus tests for model 1 for each outcome variable.

activity for a while allowed to encounter improvements not seen before, which suggests that perhaps exposure to real-life situations, far from the AR settings and after having used them, can play a role in demonstrating what the person has actually learned with PR.

All in all, the intervention with the PR games was found to be effective in improving the four evaluated skills among the autistic participants, either after the intervention or sometime after it. There are some aspects which have been considered in this study that are key for establishing evidence-based practices in autism[75] and that may have greatly contributed to the success of the intervention. Firstly, the PR games were generally engaging

Term	F	df	df (res)	p
SELF				
Center	2.403	2	17	0.121
ES	1.16	1	17	0.296
phase	2.86	3	97	0.041
center * ES	0.817	2	17	0.458
center * phase	2.993	6	97	0.01
ES * phase	1.098	3	97	0.354
center * ES * phase	0.818	6	97	0.558
Term	**F**	**df**	**df (res)**	p
IMET				
Center	8.579	2	17	0.003
ES	2.759	1	17	0.115
phase	21.906	3	97	< 0.001
center * ES	2.863	2	17	0.085
center * phase	3.024	6	97	0.009
ES * phase	0.562	3	97	0.642
center * ES * phase	3.022	6	97	0.009
Term	**F**	**df**	**df (res)**	p
IJA				
center	2.861	2	17	0.085
ES	1.442	1	17	0.246
phase	5.261	3	95	0.002
center * ES	0.973	2	17	0.398
center * phase	0.83	6	95	0.549
ES * phase	2.385	3	95	0.074
center * ES * phase	2.06	6	95	0.065
Term	**F**	**df**	**df (res)**	p
RJA				
center	2.525	2	17	0.11
ES	1.586	1	17	0.225
phase	3.153	3	95	0.028
center * ES	1.476	2	17	0.256
center * phase	2.429	6	95	0.031
ES * phase	0.573	3	95	0.634
center * ES * phase	2.001	6	95	0.073

Table 5. Fixed effects omnibus tests for model 2 for each outcome variable.

for participants. Although we did not implement any specific assessment to measure engagement, center staff who implemented the study sessions reported in the procedural fidelity protocol participants' reactions. At the beginning, as some participants did not recognize themselves, they did not pay attention to the screen and felt restless throughout the practice sessions. However, as they learnt that what was reflected on the screen was them and that they could get things with their movements, it became engaging. Participants who could not communicate with oral language indicated with non-verbal language their willingness to play the games by happily taking the laminated card or real object that took them to PR. Some also vocalized and laughed throughout the session. Participants who used verbal language to communicate even said things like "I want a game!". No participant rejected to play the PR games, even when they displayed severe behavioral disruptions such as intense stereotypical movements or occasional head hitting with their hands, which is pretty common among the target population, and how engaging an intervention is may make the difference between being effective or not[50,83]. Secondly, the professionals who know the participants best – because they teach them on a daily basis in the centers they attend – were the ones who delivered the study sessions, providing highly valued information on participants' characteristics and accommodating all the participants' communication and learning needs throughout the study. This, together with the fact that the study sessions took place where participants usually learn, provides support for the ecological validity of the current study, which in this field is very much appreciated due to the difficulties that autistic people commonly have in adapting to new settings[84].

In this article, only one hypothesis was formulated, which was addressed with data collected through the SELF, IMET, and JA Protocol assessments. However, the version of the PR used in this study was designed to collect and store data from players' performance. Once a player completes an activity, after a reward is displayed on the screen, a scoring system appears to allow the instructor to give a score to the player's performance with the

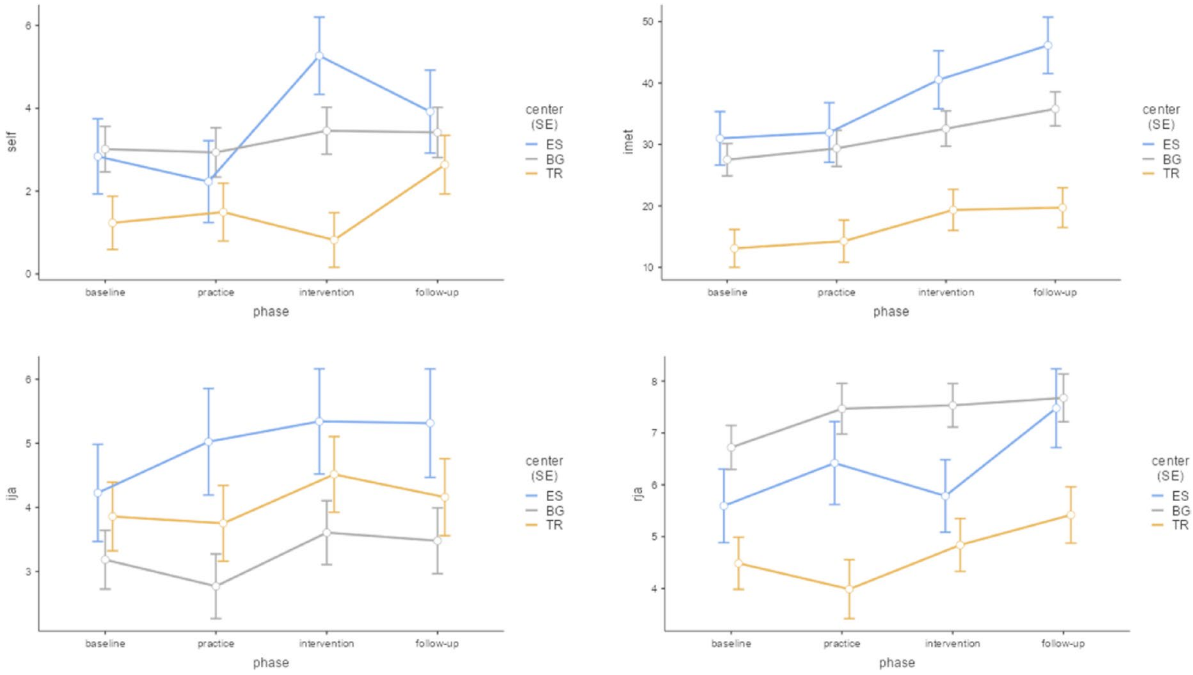

Fig. 7. The Center-by-Phase fixed effects plot per outcome variable.

following scoring: 0 points, if they did not complete it; 1 point, if they completed it with physical help; 2 points, if they completed it with verbal help; and 3 points, if they completed it without help. Also, each game was coded to register information such as the number of items or the time the player needed to complete an activity, which can be automatically recorded and stored for later analyses. All these data were collected and, at the moment of writing this manuscript, data is being analyzed for another article in which the progress of the participants within the games throughout the study will be presented and discussed. The hypothesis tested in this second article is that participants' performance in the games improved as they played (e.g., they needed fewer supports and less time to complete the games). The data analyzed is expected to also inform the PR software developers on data accuracy to make adjustments improving usability and exploring the possibility of generating reports for professional users.

The current study has several limitations. To start, the number of participants from each center was small, impeding the statistical analysis that could show differences between centers. The number of participants and the lack of a traditional control group – which we did not include following ethical principles, as having a control group would have prevented a group of children within the participating centers from benefitting from the intervention – did not allow us to use an experimental design that would have facilitated causal interpretations that with the data at hand cannot be made. Whether the use of PR games is what causes the improvements observed in body knowledge, imitation, IJA, and RJA skills in the autistic participants remains to be tested further. Another limitation is that the assessment we developed to evaluate body knowledge (i.e., SELF) was not validated, and it only evaluated self-recognition, which is a small part of the whole concept of body knowledge. Generalization of the skills to other contexts was not evaluated.

Considering the findings and the limitations, replication studies with larger samples and experimental designs that facilitate causal inference would contribute to considering PR as an evidence-based practice for autism in the future. More precisely, we suggest conducting randomized controlled trials with delayed-intervention control groups, using sample sizes determined via power analysis (e.g., using G*Power[85] to ensure sufficient statistical power to detect meaningful effects, support valid causal inferences, and strengthen both internal validity and external validity, including the generalizability of the results. Exploring cultural and educational differences in larger samples from different countries could also be interesting. In this study, five games were selected based on the skills they target (Games 1–3: body knowledge, Game 4: joint attention, and Game 5: imitation), and the effects were evaluated as a whole because the literature indicates that these skills are interrelated. However, it would be interesting to know if, after each game, there is a special improvement in the skill that that game specifically targets or also in the other skills. To test this hypothesis, more evaluations would be needed throughout the study (i.e., one evaluation just before shifting to the next game). Also, future studies in this line should consider including the PR *Gaze following* game that was found effective in improving RJA in autistic children in a previous study[66]. This game was not included in our study because, for calendar reasons, we could only include one game to work on JA skills and we chose *Learning to point* which is meant to promote both IJA and RJA, and not only RJA as *Gaze following*. However, especially considering that RJA improvements in participants were not seen until the follow up phase, we would recommend to include this other game in the intervention program as well. Finally, we suggest future research focus on the assessment tools used in this study. Regarding body knowledge, it would be valuable to validate the SELF scale to ensure its rigor in future applications. Additionally, the development and validation of more comprehensive tools for assessing body knowledge in autistic children would be highly desirable. Regarding JA, emerging validated scales for autistic children with co-occurring intellectual disability should be considered in future research to enhance assessment precision[86]. In addition, technologies such as virtual reality and eye-tracking offer promising opportunities for more effective and objective evaluation of JA in this population[87]. Other recent technological advances in the assessment of imitation in autistic children—designed to be sensitive to individual variability—are also opening new research directions[88].

While it can be interpreted that this study adopts a medical model perspective by aiming to support the development of specific skills (i.e., JA, imitation, and body knowledge) in autistic children with intellectual disability, it does so through a user-centered, co-designed technology-mediated intervention embedded in real-life educational settings. We acknowledge the value of social and environmental models, which emphasize the role of societal and contextual barriers in shaping disability. Our approach focuses on empowering participants with key skills and strategies to enhance their interaction with the environment and support participation[89]. By involving center staff in the implementation and using games which have been collaboratively developed with users, this intervention also aligns with inclusive practices and highlights the interaction between individual capacities and supportive contexts.

In conclusion, this is the first AR technology intervention program that has been found effective in simultaneously improving body knowledge, imitation, IJA, and RJA in autistic children with intellectual disability. This is a relatively short and socially valid intervention based on the use of PR, which is an openly available AR software that does not need specific training to be used and can be effectively delivered by professionals in natural settings. If other professionals and/or researchers want to implement this intervention, they can do so with the support of the documents we openly share in the Supplementary Information file. The current study was conducted according to Reichow et al.'s evaluative method[75], adds to the existing literature supporting the use of this AR tool, allows for replication studies[90], and it is suitable for being included in future meta-analytic reviews, contributing so to the promotion of evidence-based practices in the field of digital technologies for autism.

Data availability

The data presented in this study are openly available in Open Science Framework: https://doi.org/10.17605/OSF.IO/6GRJT. In detail, all the information concerning the research study's data and analyses can be found here: https://osf.io/8d4jz (accessed on 8 June 2025).

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Author contributions
P.P.-F. led this study, which was conducted in the framework of the ARBIT Erasmus + project led by G.H. P.P.-F. obtained ethical approval from her institution and coordinated the study implementation across the three par-

ticipating countries. P.P.-F., G.H., J.N., and C.T., conceptualized the study. P.P.-F. created the research design with the collaboration of G.H., J.N., C.T. and J.L. L.V. created the version of the Pictogram Room software used in this study with the collaboration of G.H. and monitored its correct functioning in the three centers. A.L.-F. led the implementation of the study in the Spanish school. M.S., Y.K., and A.A. led the implementation of the study in the Bulgarian center. S.B. and A.A. led the implementation of the study in the Turkish school with the collaboration of E.K. P.P.-F., L.V., J.N., and C.T. did the training course to A.L.-F., M.S., Y.K., A.A., S.B., and A.A. J.N. created the IMET assessment and co-created with L.V. the SELF assessment. A.L.-F. created the cognitive assessment tool to evaluate participants' intellectual disability. P.P.-F. created all the other study documents and built the databases, which were checked by A.L.-F. J.L. analyzed the data and wrote most of the statistical analysis and results sections. P.P.-F. wrote the first full draft to which all the other authors contributed. All coauthors agreed with the last version of the manuscript which was proofread by J.L.

Competing interests
The authors declares no competing interests.

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