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Augmented tabletop interaction as an assistive tool: Tidd's role in daily life skills training for autistic children

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ABSTRACT

Autistic children may often experience challenges in mastering daily living skills crucial for their independence and well-being. This study introduces "Tidd," an augmented tabletop interactive system designed to assist autistic children in practising daily living skills in an engaging and physically interactive environment. We conducted a user study in a medical rehabilitation center and an integrated kindergarten. Seventeen autistic children aged three to five years used Tidd in training sessions covering two vital skills: bed-making and dressing. Progress was evaluated through task completion and progress tracking, observational data for children, and therapist qualitative feedback. Therapists reported that Tidd was beneficial in maintaining the children's attention and enhancing their motivation. Observational data further suggested increased engagement and decreased frustration during tasks. This study with Tidd highlights the potential of tabletop interaction to support therapists in training autistic children to learn daily living skills.

1. Introduction

The prevalence of autism is continually rising and now affects approximately 1 in 36 children (Maenner et al., 2023). This underscores the urgent need for more targeted early interventions (Camarata, 2014) to improve the developmental trajectories and quality of life for individuals on the autism spectrum. Among the most critical areas of intervention is fostering autonomy, as it plays a pivotal role in enabling individuals with autism to achieve functional independence and participate meaningfully in society. Daily living skills (DLS), which include basic self-care tasks essential to personal autonomy and social integration, are central to this goal (Bal et al., 2015; Nikolopoulos, 2020). However, learning DLS is often challenging for autistic children due to their unique developmental profiles, including pervasive developmental disorders and atypical learning abilities (Nah and Ng, 2023). These challenges highlight the pressing need for engaging, adaptive, and personalised approaches tailored to their unique learning needs.

Recent technological advancements have demonstrated significant potential to assist autistic children across various domains of learning and therapy (Esposito et al., 2017; Pérez-Fuster et al., 2019; Lledó et al., 2022; Lian and Sunar, 2021). Among these, Augmented Reality (AR) is a transformative tool that merges the digital and physical worlds, creating engaging and interactive environments that provide real-time feedback and support (Billinghurst et al., 2015). For instance, AR-based interventions have been used to improve shoe-wearing (Moorthy et al., 2016) and toothbrushing skills (Zheng et al., 2021) by combining virtual participation with real-time feedback.

This paper introduces "Tidd", an AR-based desktop interactive system specifically designed to assist autistic children in mastering basic DLS such as bed-making and dressing. The system's development was inspired by feedback from therapists and autistic children at a rehabilitation center in southern China. Tidd combines digital cues with tangible props to create an immersive learning environment. This environment captures the interest of autistic children and supports the acquisition of DLS through multi-sensory engagement and real-time feedback. The content design of Tidd follows the strategy of Applied Behaviour Analysis (ABA) (Lovaas, 1987), employing storytelling to reinforce sound effects and visual cues, guiding children through tasks step by step.

To evaluate Tidd's effectiveness in enhancing DLS in autistic children, user studies were conducted at a rehabilitation hospital and an

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inclusive education kindergarten. A total of 17 children aged three to five years voluntarily participated in the study. This study was supervised by therapists and included a learning, verification, and physical practice stage, with each session lasting about one hour. Key outcome measures were the task completion time, accuracy, and the level of assistance required across training sessions. Additionally, semi-structured interviews with four senior therapists provided qualitative feedback. Results indicated a positive effect on participants' DLS task performance, with most children completing all tasks and requiring fewer prompts in the post-study validation phase. Video coding also highlighted the children's participation and enthusiasm during the study. Therapists noted the system's appeal to autistic children and provided valuable suggestions for future design improvements. These findings suggest that Tidd's AR-based intervention could effectively enhance the learning and practice of DLS in autistic children, potentially boosting their independence and self-confidence.

This paper addresses the following research questions: (1) Is the Tidd prototype effective in enhancing DLS in autistic children? and (2) Can AR be a valuable approach for teaching basic daily life activities to autistic children? To answer these questions, the paper examines the role of interactive technologies in enhancing interventions for autistic children, specifically focusing on Tidd's design, implementation, and evaluation. The primary goal of this paper is twofold: First, to evaluate the effectiveness of Tidd, an advanced tabletop interactive device, in teaching bed-making and dressing skills to autistic children. Second, to explore the potential of AR-based systems in improving intervention strategies for autistic children and contributing to more effective treatment methods based on feedback and insights from professionals.

The paper is structured to first explore the role of interactive technologies in autism treatment, review relevant literature, and highlight the motivation for utilising AR interaction in this context. The System Design and Development section delves into the design and implementation of Tidd, emphasising its AR-based features that enhance engagement and provide real-time feedback. The Methodology and Results sections present findings from a user study involving 17 autistic children and four therapists, integrating observational data, quantitative analysis, and therapist feedback to evaluate the system's effectiveness. Finally, the paper explores the study's implications, suggests potential directions for future research on AR and tangible interactive technologies for personalised autism interventions, and acknowledges the limitations of the current approach.

2. Background and related work

Teaching DLS to autistic children is critical to their functional independence and overall quality of life (Emily and Grace, 2015; Shipley-Benamou et al., 2002). These skills cover a range of activities, including personal hygiene, housework, time management, and social interaction (Wrobel, 2003; Pierce and Schreibman, 1994; Dogan, 2023). However, autistic children often have difficulty acquiring and generalising these skills due to deficits in social communication, sensory processing, and executive functioning (Khaledi et al., 2022). Therefore, targeted interventions must address these challenges and promote skill acquisition. In traditional approaches, educators and therapists use personalised instruction (Vallefuoco et al., 2022), visual supports (Dyrbjerg et al., 2007), and structured environments (Holmqvist, 2009). They also employ task analysis (Hayek and McIntyre, 2019) and reinforcement strategies (Anderson and McMillan, 2001) to train autistic children, helping them to cope more effectively with daily challenges and improve their quality of life.

2.1. Current technologies and tools in training daily living skills for autistic children

The integration of technological innovations to promote the development of DLS in autistic children is a rapidly growing area. Current research and practices demonstrate the effectiveness of tools like computer and tablet applications, which use visual scheduling and digital social stories to provide structure and clarity for daily routines (Esposito et al., 2017; Pérez-Fuster et al., 2019). AR interventions have shown particular promise, offering increased engagement in daily tasks by creating immersive and interactive learning environments (Lledó et al., 2022; Lian and Sunar, 2021).

Numerous AR and non-AR applications have been developed to support autistic children, each with distinct strengths. For instance, FaceMe (Li et al., 2023) leverages AR and virtual agents to improve emotional and communication skills by teaching children to recognise facial expressions. Similarly, AR-based tools like CheerBrush (Zheng et al., 2021) enhance toothbrushing skills through virtual engagement and real-time feedback, reducing stress and improving learning outcomes. While these applications are effective in specific domains, they are often task-specific and lack flexibility in addressing broader skill sets such as DLS. Other studies have explored multi-sensory and interactive designs. BendableSound (Cibrian et al., 2017) uses a tactile interface to support music therapy and motor coordination, while FroggyBobby (Caro et al., 2017) employs gamified exercises to improve eye-body coordination. However, these tools primarily target sensory-motor skills rather than functional daily living tasks.

Despite these advancements, gaps remain in providing integrated, flexible, and engaging solutions for training DLS. Many existing tools focus on single-task interventions, lack real-time adaptability, or require significant caregiver involvement to deliver consistent outcomes. Additionally, the application of AR for DLS training remains underexplored in areas such as bed-making and dressing, which are critical to fostering autonomy. Our system addresses these gaps by combining AR technology with an interactive tabletop interface designed specifically for training bed-making and dressing skills—two essential components of DLS. Unlike existing applications that are often limited to sensory or emotional training, Tidd offers a multi-stage learning process (learning, verification, and physical practice) tailored to the unique needs of autistic children. Its design is informed by therapist and caregiver input, ensuring the system aligns with real-world practices and is adaptable to various skill levels.

2.2. Challenges and opportunities in using tabletop interaction for autistic children

The integration of tabletop interactions in autism interventions has garnered attention due to their tactile and spatial advantages (Atherton and Cross, 2021; Winoto and Tang, 2019; Hasan and Islam, 2020). Researchers have noted the ability of tabletop interfaces to foster cooperative and shared experiences (Wu et al., 2022), which is crucial for autistic children who often struggle with social interactions (Weiss et al., 2011; Silva-Calpa et al., 2018). However, there are significant challenges associated with such interventions. Top among these is the sensory overload some autistic children might experience (Leffel, 2022; Hassan, 2024), given the multi-modal feedback often inherent in tabletop activities. Yet, opportunities abound. For instance, the tactile nature of tabletops allows for tangible interactions, suitable for many autistic children who prefer physical interactions with objects (Wu et al., 2022; Bonillo et al., 2019). iCAN (Chien et al., 2015) is a tablet-based teaching system designed to enhance the communication skills of autistic children. It combines the PECS approach with digital visualisation and speech capabilities, aiding caregivers and therapists in improving autistic children's learning and interaction abilities. Moreover, the customisable nature of digital tabletop interfaces allows therapists to adapt interventions to each child's specific needs, enabling personalised therapy sessions (Silva et al., 2014; Hassan and Pinkwart, 2019; Ahsen et al., 2022). While challenges persist, the potential of tabletop interactions in providing compelling, engaging, and tailored Autism Spectrum Disorder (ASD) interventions is a growing area of exploration.

Research in this area includes the development and evaluation of computer-enabled tabletop learning tools specifically designed for autistic children. These have shown promising results regarding effectiveness, efficiency, and satisfaction among participants in special education environments (Hasan et al., 2023). For example, engagement with tabletop role-playing games (TTRPGs) has been identified as a beneficial avenue for autistic young adults to enhance social skills, foster relationships, and build a sense of community (Parks and Parks, 2023). Similarly, A tabletop game called CoASD (Silva-Calpa et al., 2018), tailored for enhancing collaborative skills among autistic children, has shown significant promise in improving social interactions and cooperative abilities. The "Hand-in-Hand" system exemplifies the innovative application of collaborative virtual reality (CVE) technology in promoting social interaction and communication through interactive games and gesture-based collaboration, specifically designed for children with ASD (Zhao et al., 2018). In addition to these technological interventions, research conducted by Hasan and Islam (2020) has identified key design considerations for developing an interactive tabletop learning tool for autistic children, emphasising usability and user experience. We aim to develop engaging and effective training tools to assist therapists in working with children, thereby improving outcomes in learning daily life skills.

While previous works offer a comprehensive understanding of interactive technologies for DLS connections in autism, there remains a distinct gap in their application in specific environments, notably the tabletop interface. Many studies have underscored the benefits of interactive technologies, such as AR platforms, in improving daily living skills among autistic children (Ip et al., 2018; Kung-Teck, 2020; Antão et al., 2020). However, the tabletop environment, a ubiquitous and accessible platform, has received comparatively limited focus, especially in designing technologies tailored for autism intervention on training DLS. Recognising this gap, our research aims to innovate within this space, seeking to design projected interactive tabletop experiences to assist autistic children in forging stronger connections with essential daily living skills.

3. System design and implementation

3.1. Preliminary study

3.1.1. Requirement analysis and design specification

Before initiating the preliminary study, we conducted a comprehensive requirements analysis to understand the specific needs of autistic children and the challenges therapists face when teaching DLS. Input from therapists, parents, and special education experts highlighted key areas needing improvement in current training methods. First, bed-making and dressing were identified as essential skills for fostering personal independence, yet their complexity often leads to their exclusion from institutional training. Second, autistic children frequently struggle to grasp abstract instructions and follow live demonstrations, which requires incorporating visual reinforcement and tangible interactions to aid comprehension. Third, therapists emphasised the importance of repetitive practice and positive reinforcement to maintain motivation and encourage skill acquisition. These findings formed the foundation of our design, which integrates storytelling, AR animations, and tangible interaction elements. Additionally, tasks were broken down into smaller, more easily imitated steps to simplify learning and gradually build competence.

3.1.2. Prototype design and preliminary study

Based on the initial requirements obtained from therapists, we developed a low-fidelity AR desktop interactive system designed to help autistic children master bed-making and dressing skills (as shown in Fig. 1). The main features include storytelling elements to provide context, AR-based animations for visual reinforcement, and tangible props for hands-on practice. Specifically, the storytelling component introduces relatable scenarios linked to essential life skills, such as getting ready for bed or choosing clothing appropriate for different seasons, enhancing children's initial understanding and interest. The AR-based animations visually demonstrate each procedural step (e.g., a story about a cute rabbit going to bed at night and waking up in the morning teaches children step-by-step how to do bed-making), offering clear and engaging visual cues to guide the children's actions. Tangible props, such as miniature quilts and clothing items, enable children to imitate and practice each demonstrated step physically, thus facilitating better knowledge transfer. Additionally, the system incorporates interactive prompts and feedback mechanisms to reinforce children's learning and sustain their engagement throughout the tasks.

We conducted a pilot study at an autism rehabilitation center to evaluate the system's usability and collect feedback for further improvement. The study involved 22 participants, including 13 autistic children (aged 5–12), seven therapists, and two parents. During the study, children were first introduced to the interactive system and guided through structured tasks, such as folding a mini quilt or selecting seasonally appropriate clothing. In a subsequent phase, the children practised these tasks using real-world props in an adjacent space, enabling us to assess their ability to transfer newly acquired skills to real-life settings. Throughout the study, therapists and parents provided qualitative feedback through semi-structured interviews, offering valuable insights into the system's effectiveness and areas needing improvement.

3.1.3. Results and observations

The study revealed several key findings that inform future improvements to the system. First, combining visual reinforcement with tangible interaction proved highly effective in engaging children and enhancing their understanding of tasks. AR animations and projector cues offered clear, step-by-step instructions, while tangible props bridged the gap between virtual and real-world tasks. Second, integrating positive sensory feedback, such as fireworks animations and applause, successfully motivated children to complete tasks and maintain focus. However, therapists noted the need for more customisation of the reward mechanisms to suit individual preferences. Third, the structured learning approach guided by ABA principles facilitated skill acquisition, but carefully balancing guidance and independence is necessary. In particular, gradually transitioning from guided learning to independent practice is crucial for enabling the generalisation of skills. Feedback from therapists and parents underscored the importance of designing training environments that simulate realistic scenarios, ensuring that the skills learned are both practical and transferable.

3.2. Task learning of daily living skills task

Before designing the instructional content, we referred to the Compulsory Education Curriculum Standards for Special Education Schools (2016 Edition).[1] To ensure coherence and relevance, we developed a day-starting curriculum that includes activities such as getting up, bed-making, and dressing, closely aligning the instructional content with the children's daily routines. Early intervention for autistic children is widely recognised as crucial for fostering adaptive functioning and daily living skills, which are the foundation for independence and long-term development (Holtz et al., 2006). Therapists and healthcare professionals emphasise that starting training early takes advantage of children's neuroplasticity and heightened capacity for learning. Our approach integrates these principles in Chinese early education, where children are encouraged to develop independence and responsibility beginning in kindergarten. By breaking down tasks into manageable steps tailored to individual abilities, the curriculum supports personal development and enhances the children's ability to integrate into mainstream educational environments.

[1] http://www.moe.gov.cn/srcsite/A06/s3331/201612/t20161213_291722.html.

Fig. 1. Child participants experience low-fidelity prototype system in pilot study.

Throughout the learning process, a therapist guides and supports the participants as they interact with the system. The therapist's primary role is to assist children in understanding how to use the system and complete the task workflow. While the therapist provides guidance during the initial stages, such as explaining the tasks and demonstrating their execution, their involvement decreases as the participants progress to more independent stages. In the final two steps of the bed-making and dressing task, the therapist observes the participants' performance without directly intervening. If a participant encounters difficulties, the therapist offers minimal guidance, primarily by directing them back to earlier learning stages for additional practice. This approach ensures that children gradually transition from guided learning to independent task completion while maintaining support where necessary.

3.2.1. Bed-making

This part outlines a four-stage learning process for teaching participants how to arrange quilts: (1) A story context with sound effects and animations introduces the task. Participants are shown how to arrange bedding through a demonstration, with successful attempts affirmed by a fireworks animation. (2) Participants learn to fold a mini quilt in five steps, demonstrated via animation and projector cues. Correct folding is encouraged with a fireworks animation. (3) With the tablet turned off, participants rely on AR projection cues to replicate the bed-making process twice, with guidance provided as needed. (4) Depending on the participant's readiness, they attempt to fold a regular-sized quilt unaided within three minutes, with possible guidance back to learning stages and rewards upon completion.

Tablets are used to demonstrate the dynamic folding process through animations, making the instructions clear and easy to understand. These animations visually break down each step, ensuring participants grasp the required order and actions. The practice step enabled us to assess their ability to transfer the skills learned in the AR interactive environment to their actual daily environment, which was crucial to verify the effectiveness and practicality of the intervention (see Fig. 2).

3.2.2. Dressing

The tutorial for the Personal Dressing Game is structured into four sections, aimed at teaching children how to select appropriate clothes for summer, autumn/spring, and winter. (1) Utilises storytelling to introduce seasonal dressing with vivid seasonal images and animations, starting with the current season and leading into summer. (2) Offers interactive learning through clothing cards for each season, where participants match cards to projected silhouettes and dress cartoon characters in a specific order, guided by visual cues like outlined projections with numbered hints for sequence and blue dotted boxes for placement. Correct placements are confirmed by changing outlines, star animations, and auditory cues. (3) Challenge participants to apply what they have learned by dressing characters without numerical hints and in a randomised seasonal order, encouraging independence. (4) This step involves the child's physical clothing selection and sequencing, based on drawn season cards, with a time limit of 5 min. Errors lead to a learning phase repetition, and successful completion is rewarded (see Fig. 3).

3.3. Interactive design

3.3.1. Storytelling

Storytelling is widely accepted and utilised in children's education as an educational and guidance tool, especially for autistic children. This approach allows children to understand and grasp new knowledge through vivid situations (Sambak et al., 2021; Fallahi-Khoshknab et al., 2021; Ying et al., 2016). Research has already shown that the narrative approach, through storytelling, can more effectively capture the attention of autistic children and enhance their learning (Pham et al., 2022; Franke and Durbin, 2011). AR technology can make children feel like they are part of the story, thus increasing their interest and engagement in learning. Integrating learning content into a context not only aids in better skill mastery but also in the development of emotions and empathy. In our system, when teaching children how to prepare their bedding, we describe a little boy's daily routine, including going to bed, waking up, getting dressed, and folding the quilt. This helps

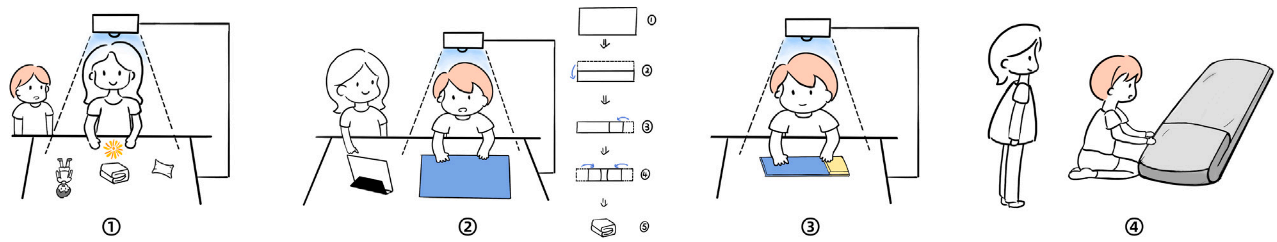

Fig. 2. The process of dressing bed-making learning: (1) Storytelling background; (2) Steps to fold a mini quilt; (3) Practice folding mini quilts without prompts; (4) Standard-size quilt practice.

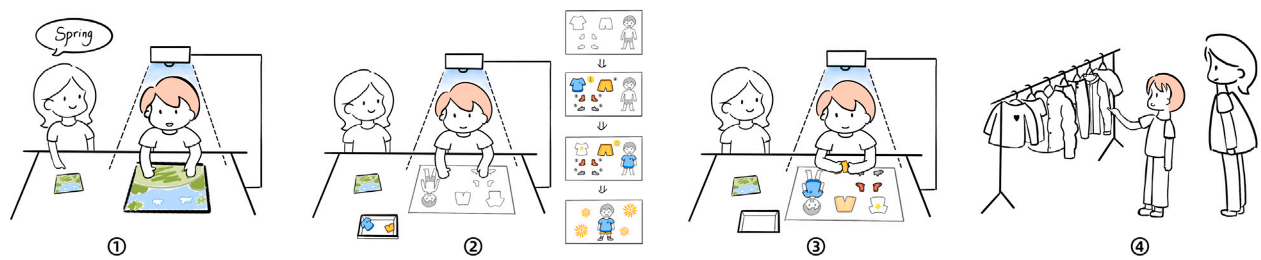

Fig. 3. The process of dressing learning: (1) Seasonal storytelling; (2) The steps of learning; (3) Process practice without cue cards; (4) Seasonal clothing matching.

participants understand the reasons behind making the bedding and learn the method and order of doing so. When teaching children how to choose appropriate clothing, by describing different seasons, children can more easily grasp why and how to select suitable clothing according to the season. Choosing a little boy as the story's main character, rather than an animal or a virtual cartoon character, aims to enhance empathy and make it easier for children to engage with the story, enabling them to understand better and master the learning content.

3.3.2. Intervention strategies and reward system

Through comprehensive consultations with therapists, our intervention strategies integrated ABA (Lovaas, 1987), we decomposed complex daily living tasks such as bed-making and dressing into clear, manageable units. This allowed children to gradually master skills through progressive successes, enhancing confidence and promoting skill generalisation. To effectively accommodate autistic children's strong preference for visual stimuli, tablets provided visual reinforcements featuring captivating animations and dynamic motion effects. Projected visual cues were also strategically employed to highlight critical tasks, ensuring clarity and maintaining engagement during task completion. Audio prompts complemented these visual guides, offering additional auditory support to cater to varied learning preferences and helping children stay focused throughout tasks.

Recognising the diverse and individualised preferences among autistic children, our reward system incorporated flexible, personalised reinforcement strategies inspired by therapist recommendations. Timely positive sensory feedback – including vibrant animations like fireworks, applause sounds, and playful audio effects – celebrated successful task completions, motivating continued participation and progress. To further personalise the intervention, therapists and caregivers could customise physical rewards according to each child's specific interests and sensitivities. For instance, while some children found elaborate animated celebrations rewarding, others preferred simpler visual cues or non-visual forms of acknowledgement. Additionally, milestone achievements were acknowledged through customised "surprise boxes",
thoughtfully filled with engaging items such as building blocks, stationery, glowing paper, or tactile toys. These tailored reinforcements and structured task breakdowns and multimodal sensory cues directly addressed autistic children's unique learning styles, ensuring an engaging, supportive, and effective learning environment.

3.3.3. Interaction design and tangible objects

We use tangible interaction with real miniature props to allow children to use natural objects and a projected interface intuitively. This combination of real and virtual can help autistic children to better understand and communicate. Secondly, to ensure a better experience for the children using the projector, we have set up a larger size for the operating interface. This makes it easier for children to click and touch the interface, especially for those with fine motor coordination difficulties. Furthermore, the projection of our desktop onto a matte, flat surface, along with the lighting and brightness of the experimental environment, were carefully adjusted to minimise eye irritation. Finally, augmented reality features add more interactivity and fun to this design, such as enhanced visual stimulation with kinetic and sound effects. Participants can interact with real props and see how the virtual elements interact with physical objects, thus providing them with a fun and educational experience.

3.4. System development

Our system was built on the previous interaction prototype by Wu et al. (2023) but updated to improve stability and system integration. The hardware components of this system use LOGITECH high-definition cameras for the real-time capture of participant behaviour and physical props. The system then displays the user interface through desktop projection. The software component, which consists of interactive scenes integrated with OpenCV and Halcon library functions for precisely identifying and matching feature points on physical toys, is developed on the Unity platform. Our research team handcrafts these physical toys(details see Fig. 4).

- In the "bed-making" phase, item recognition is accomplished using Python and OpenCV. We initially identified the unobscured part of the blanket through colour filtering. Only when this area is smaller than a preset value do we proceed to filter out the location of the blanket obscured by projection. Next, we calculate the contour size of this area and compare it with preset standards. The system deems the mini blanket successfully made if it falls within an acceptable error margin. A client/server (C/S) architecture establishes communication between Python and Unity. A fireworks effect is played as encouragement once the participant correctly executes the operation on the interface.

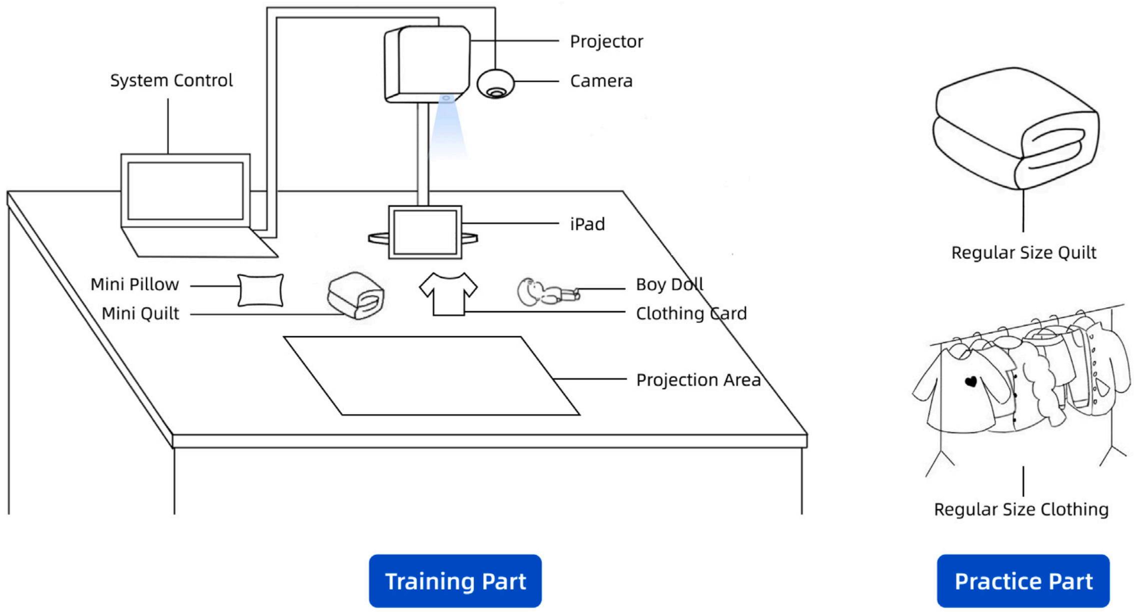

Fig. 4. System architecture diagram of Tidd.

- In the "dressing" phase, the system assesses whether the user accurately places the clothing cards in specific locations. We employ scale-invariant template-matching technology from Python, OpenCV, and the HALCON library to achieve this, comparing real-time images with predefined template images. After setting the relevant parameters, functions are called to obtain matching results. Based on the positional relationships of these matching results, the system further evaluates whether the user has correctly placed the cards. The correct clothing numbers are then transmitted to Unity, providing immediate feedback to the user.

4. Field study methodology

This study aimed to evaluate the effectiveness of a tabletop AR interactive system combined with storytelling in teaching life skills such as bed-making and dressing to autistic children and to explore the potential of this research in assisting therapists in their instructional roles. The study was conducted at a children's rehabilitation center and a public kindergarten with inclusive education in Beijing, China. The study lasted three days, one at the rehabilitation center and two at the kindergarten. Institutional Review Board (IRB) approval was obtained from the Peking University (IRB00001052-20005), and the parents signed consent forms before the commencement of the study.

4.1. Participants

Child participants comprised 17 children: 15 boys and 2 girls, with an age range of 3–5 years, as shown in Table 1. A total of four therapists aged 29–42 participated in our on-site interviews. Details are shown in Table 2. We collaborated with rehabilitation agencies and inclusive education schools, asking them to invite parents of autistic children via social media to sign up for the study voluntarily. All participants were diagnosed based on the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5) (APA, 2013) criteria. Their diagnoses were further validated at a local hospital using standardised assessment tools such as the Childhood Autism Rating Scale - Second Edition (CARS-2) (Schopler et al., 2010), Modified Checklist for Autism in Toddlers, Revised (M-CHAT-R) (Robins et al., 2009), and the Autism Behaviour Checklist (ABC) (Krug et al., 1980). The cohort consisted of 12 children with low needs, four with moderate needs, and one with high needs. To ensure the fairness and accuracy of our study, we verified that none of the participants had been involved in similar studies before this one. After the study, each participant received a blind box gift valued between $3–7, containing items like building blocks, stickers, stationery, and plastic toys.

4.2. Procedure

Upon arrival at our usability space, parents were informed about the study's objectives and signed informed consent forms. With the parents' written and oral consent, we video-recorded the entire study process. Before the children operated the system, we briefly interacted with the parents to understand each child's basic situation and their mastery of life skills. We also invited three therapists to join us in the same space: one to supervise our study process, one to assist the children with operational steps during the study, and another to soothe the emotions of the autistic children, ensuring the smooth conduct of the study. Based on the children's cognitive abilities and the therapists' recommendations, the children were allowed to choose between the themes of bed-making or dressing.

We initiated one-on-one interactive teaching sessions with child participants under the guidance of therapists. We began by introducing the background to the children through storytelling combined with AR projection, then used physical props and AR projection cues to teach life skills in a gamified manner, and finally, based on the therapists' assessment, decided whether to involve the children in the final validation with physical props. Each participant's entire interaction time lasted about 30 min. During the teaching, we emphasised the appearance of animations and sound effects to draw the children's attention to these changes and observe their responses to the system. In the bed-making study, there are four stages: two learning stages, one mini prop verification stage and one regular-sized prop practice verification. In the dressing part, there are six stages: three learning stages corresponding to three seasons, two random season verification stages, and one practice verification. At the end of the children's system experience, we conducted semi-structured interviews with the therapists to comment on their behaviour and understand their attitudes towards comparing this system with their regular teaching methods. It also discussed the potential applicability of the system in teaching life skills. We recorded the children's conditions and the parents' contact information for future communication after the study. A total of three researchers were involved: a female researcher guided the child participants and conducted

Table 1
Autistic children participant details form.

ID	Gender	Age	Category	Diagnosis	Place
P1	Male	5	Bed-making	Children with low support needs	Autism rehabilitation center
P2	Male	3	Bed-making	Children with middle support needs	Autism rehabilitation center
P3	Male	5	Bed-making	Children with low support needs	Autism rehabilitation center
P4	Male	3	Bed-making	Children with low support needs	Autism rehabilitation center
P5	Female	3	Bed-making	Children with middle support needs	Autism rehabilitation center
P6	Male	4	Bed-making	Children with low support needs	Autism rehabilitation center
P7	Male	4	Bed-making	Children with low support needs	Autism rehabilitation center
P8	Female	5	Bed-making	Children with high support needs	Autism rehabilitation center
P9	Male	4	Bed-making	Children with middle support needs	Autism rehabilitation center
P10	Male	5	Bed-making	Children with low support needs	Autism rehabilitation center
P11	Male	4	Dressing	Children with low support needs	Autism rehabilitation center
P12	Male	4	Dressing	Children with middle support needs	Autism rehabilitation center
P13	Male	5	Dressing	Children with low support needs	Integrated kindergarten
P14	Male	5	Dressing	Children with low support needs	Integrated kindergarten
P15	Male	5	Dressing	Children with low support needs	Integrated kindergarten
P16	Male	4	Dressing	Children with low support needs	Integrated kindergarten
P17	Male	5	Dressing	Children with low support needs	Integrated kindergarten

Table 2
Therapist profile form.

ID	Gender	Age	Exp. (Yrs)	Type of treatments	Work place
T1	Female	29	4	Behavioural Therapy; Family Support	Autism rehabilitation center
T2	Female	33	7	Cognitive Behavioural Therapy; ABA	Autism rehabilitation center
T3	Female	38	12	ABA; Speech Therapy	Integrated kindergarten
T4	Female	42	14	Educational Therapy; Speech Therapy	Integrated kindergarten

the teaching, a male research assistant focused on the operation of the system's software and hardware, and another female researcher was responsible for communicating with the parents about the children's conditions and documenting the study process.

4.3. Data collection and analysis methods

We employed field observations and semi-structured interviews in this study. Child participants interacted with a prototype application while their interactions were recorded using hidden cameras fixed in the corners. Following their interaction, semi-structured interviews of approximately 20 min were conducted with therapists and special education teachers to gather insights about their experiences, children's behaviours, and perspectives on our system. The data comprised 25 GB of video content and 105 min of audio recordings, iflyre[2] was used by us to convert the audio to text. Quantitative data were reported using the Feldman analysis tool. Observational data were coded according to the children, the tabletop system, and the therapists. Thematic analysis was utilised to analyse the interview transcripts, identifying key aspects of the children participants' behaviour, their interaction with the system, and therapists' feedback. Initial codes were generated and then grouped into broader themes: (1) Children's task completion rates and progress in activities like bed-making and dressing in the study setup; (2) Observational data concerning children's engagement and challenges faced when using the tabletop augmented reality system; (3) Qualitative feedback from therapists, including their comments and recommendation on the system and comparisons with their traditional teaching methods. Three researchers independently coded the data to ensure inter-rater reliability, with any discrepancies resolved through discussion.

4.4. Task completion and progress tracking

We structured the task completion assessment into three distinct phases: the learning phase, the verification phase, and the hands-on practice phase. Each child participant's task completion was quantified by counting the number of verbal and gestural prompts provided by researchers and therapists. Verbal prompts included: (1) utilising directional terms such as "left" and "right" to indicate the correct placement orientation; (2) employing colours and numbers to hint at the cards to be selected; (3) using feedback terms like "correct" or "incorrect" to provide timely reminders; (4) directly indicating the items to be chosen with nouns such as "clothes" and "socks". Gestural prompts encompassed: pointing or dragging objects to assist children with the next step while encouraging them to mimic the action; and grabbing the child's hand to maintain focus and guiding it to the correct position.

Task success was operationalised based on the intervention rate, calculated as the sum of verbal and gestural prompts divided by the total number of steps for each task. Fewer prompts indicated higher task success, reflecting the participants' ability to perform tasks with reduced external guidance. After excluding children who did not complete all steps, we conducted an in-depth analysis of data from 11 tasks, including Bed-making (P1, P3, P6, P7, P8, P9) and Dressing (P12, P13, P14, P15, P16). The data for each task is presented in Table 3. We applied the Friedman test, a non-parametric method suitable for comparing related samples. This allowed us to evaluate whether there were statistically significant differences in intervention rates across the different stages (e.g., learning stage [LS1], verification stage [VS], and practice verification [PV]). Pairwise comparisons were then performed to examine specific differences between stages. The comparison between LS1 and other stages was particularly relevant, as LS1 represents the initial stage where participants are unfamiliar with the tasks. By comparing LS1 to subsequent stages, we aimed to assess the impact of different experimental conditions (e.g., increasing familiarity and practice) on task success.

Since the data were not normally distributed, as determined by descriptive analysis in SPSS (IBM Corp, 2017), we performed Friedman's test on the dataset (Friedman, 1937). We found a statistically significant difference between the different stages of children's learning bed-making (χ^2 = 10.582, p = 0.005, Kendall's W = 0.353) and dressing (χ^2 = 13.791, p = 0.001, Kendall's W = 0.459). These effect sizes indicate moderate to strong effects for the staged learning interventions. To further compare potential differences across various stages, which reflect children's performance during the study, we analysed the results using medians and pairwise comparisons for each stage. To mitigate the risk of Type I error resulting from multiple comparisons, we applied the Bonferroni correction during the experiment. This is a widely accepted

[2] https://www.iflyrec.com/.

Table 3
Statistics on task completion.

Project	Stage					
Bed-making	LS(Learning Stage)1	LS2	VS(Verification Stage)	PV(Practice Verification)		
Step count	5	5	5	5		
Dressing	LS1	LS2	LS3	VS1	VS2	PV
Step count	6	7	9	7	6	4

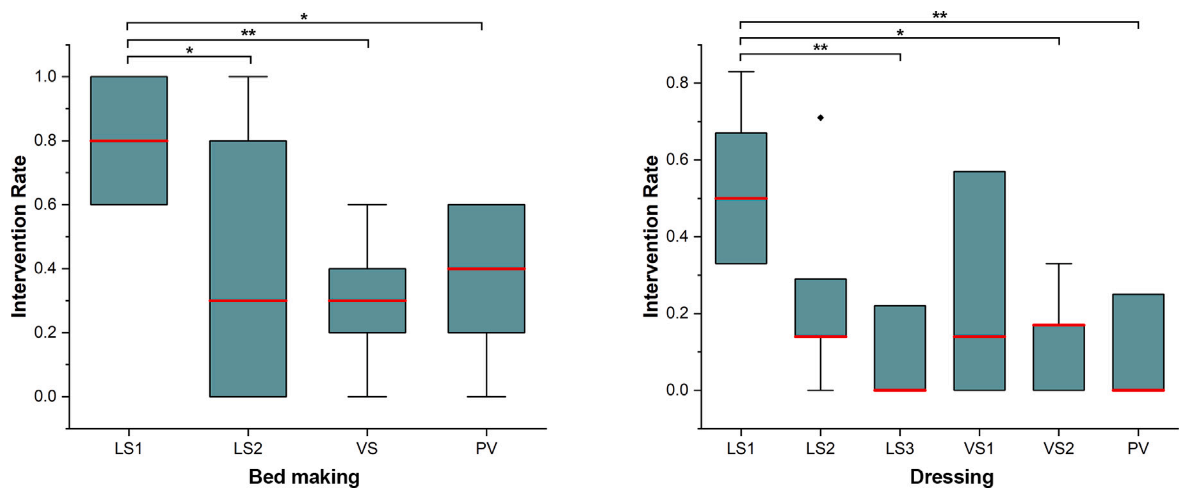

Fig. 5. Plot of intervention rate against bed making and dressing.

method to adjust the significance threshold when multiple tests are conducted, reducing the likelihood of false positives. Our statistical results are shown in Fig. 5. For bed-making, as illustrated in graph Lift, there was a significant reduction in the intervention rate across stages. Between LS1 and LS2, a significant difference was observed ($p = 0.014$, Kendall's $W = 0.298$), indicating a reduction in the need for interventions. Similarly, significant differences were noted between LS1 and VS (Verification Stage) ($p = 0.007$, Kendall's $W = 0.318$) and LS1 and PV (Practice Verification) ($p = 0.014$, Kendall's $W = 0.302$). These results suggest that children required fewer prompts as they progressed through the stages, reflecting improved task performance.

For dressing, box plots for each stage (graph Right) show a similar trend. A significant difference was observed between LS1 and LS3 ($p = 0.002$, Kendall's $W = 0.402$), indicating substantial improvement by the time children reached LS3. Additionally, significant differences were found between LS1 and PV ($p = 0.007$, Kendall's $W = 0.375$) and LS1 and VS2 ($p = 0.018$, Kendall's $W = 0.341$), highlighting consistent improvements in children's ability to dress with minimal intervention as they advanced through the stages. These results, supported by moderate to strong effect sizes, demonstrate that the staged learning and practice approach effectively enhances children's performance in both bed-making and dressing tasks.

5. Results

5.1. Observational data: Engagement and frustration

5.1.1. Storytelling in AR: Boosting child engagement and learning

The qualitative analysis of the video categorisation and coding reports revealed a significant level of interest and engagement among children in the storytelling segment of the study. Most participants showed a positive inclination and participation towards the narrative part of the system (see Fig. 6). Specifically, when facilitators and therapists posed questions about the story's details, five children responded actively, providing preliminary evidence of the story's appeal. Additionally, two of the children were able to proactively identify and describe elements within the animations, such as "it's snowing", "there is a snowman", and "there is a squirrel". This indicates that this pedagogical approach can stimulate children's observational and expressive skills. Further analysis showed that four children paid high attention to the story content, which extended beyond visual focus to an immersive engagement with the narrative. For instance, after a small boy doll was removed during the storytelling, one child continued to track the whereabouts of the doll. Most notably, three children completed folding blankets without direct prompts or instructions, learning through the story's plot. For example, when the system played the sound effect of "night falling", participants would spontaneously cover the doll with a blanket; similarly, when the system projected the image of the sun rising, they would uncover the blanket and arrange the doll. This demonstrates that integrating tabletop AR with storytelling captures children's attention and enhances their autonomous learning capabilities.

5.1.2. Animations and sound effects enhance children's engagement

Animations and sound effects served as visual rewards in this study, captivating the attention of twelve children towards desktop animations. Their expressions and gestures – ranging from laughter, waving, clapping, attentively watching animations, leaning closer to the desktop to observe, touching, and tapping the projected animations – reflected their excitement. This enthusiastic engagement indicates the effectiveness of visual rewards in capturing children's attention and eliciting positive emotional responses, which could potentially enhance their motivation to learn. During the bed-making learning task, the appearance of fireworks animation produced visible joy in six children, with three of them excitedly exclaiming, "Fireworks!" or "There are fireworks again!" Such verbal expressions and emotional reactions highlight the visual effect's efficacy in attracting children's attention and stimulating positive emotions, potentially boosting their learning motivation.

Moreover, P3 exhibited joy and anticipation for the fireworks animation after completing each step of the bed-making task, demonstrating the behaviour of seeking immediate feedback after task completion. This reflects the significant role of positive feedback the AR system provides in maintaining children's interest in learning. In the dressing task, P16 noticed that the animated child would display an unhappy expression when a wrong card was placed, prompting him to reconsider

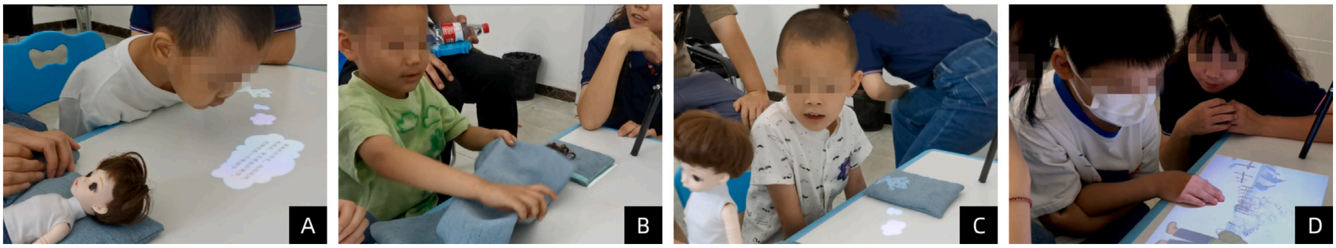

Fig. 6. Storytelling in Tidd: (A) P2 approached the projection to observe the story content closely and listened attentively to the background story. (B) P9 took the initiative to cover the boy doll with a mini quilt. (C) When the researcher moved the boy doll to the side, P7's eyes continuously tracked it to follow the story. (D) P11 actively described the background story by watching the animation.

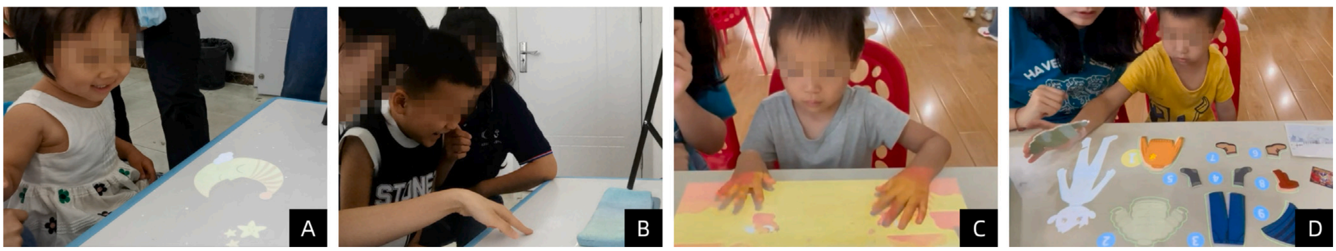

Fig. 7. Animations and sound effects enhance children's engagement: (A) P5 showed a happy expression after seeing the animation appear. (B) P1 felt very excited and saw fireworks effects after completing the task. (C) P14 really liked the animation effects and tried to touch them with their hands. (D) P16 kept trying to replay the cards to see the animation effects.

and select the correct card. P13 and two other children showed an awareness of the instructional role of numbers and sounds, respectively, indicating when numbers disappeared during the validation phase, they would actively inquire about their whereabouts. Additionally, two participants attempted to locate the source of sounds, demonstrating curiosity about audio effects. During the bed-making task, P16 repeated the mnemonic heard and followed it while performing the task. In the dressing learning task, four children proactively named the articles of clothing following audio cues, such as "pants" and "down jacket"(see Fig. 7). This not only proves the effectiveness of sound effects as teaching aids but also showcases their potential to assist children in connecting actions with memory.

5.1.3. Exploring sensory and exploratory learning through tangible props

The behaviours children exhibit during the engagement with physical props, offer insightful observations into their sensory engagement and learning processes. Particularly in bed-making, three children showed a pronounced interest in physical props, as evidenced by their interaction with dolls and the touching and kissing of the mini quilts. P1 displayed a keen interest in the mini blanket, undertaking an additional round of quilt folding on the table after completing the physical task. In the dressing task, five children demonstrated more proactive exploratory behaviours. They spontaneously reached for the clothing cards before the researchers could hand them over and began to independently assemble them or earnestly attempted to align these cards with the projected frames on their own (see Fig. 8). These actions report the children's active participation in interactive tasks and their inclination towards exploratory learning, highlighting the significant role of tangible interaction in fostering engagement in autistic children.

5.1.4. Interactive task frustrations in child learning

Our system is not perfect, particularly when catering to the complex needs of autistic children who require intensive support. Frustration among children during interactive tasks can manifest in various forms, reflecting the challenges they encounter in engaging with digital and physical elements. Firstly, the allure of the projected light was significant for some children with stereotyped behaviours, who resisted any attempts to cover it with a quilt, actively pulling the quilts away. This indicates a conflict between the intended use of the props and the children's fascination with the projection itself. Secondly, the fireworks feedback mechanism seemed insufficiently captivating for children with attention disorders, suggesting that the visual cues provided did not consistently capture their attention or were not intuitive enough to elicit the expected response. This highlights the importance of designing feedback that is both engaging and clearly connected to the children's actions. The use of double-sided cards introduced confusion among the participants. The ambiguity of having two options on a single card without clear instructions can lead to uncertainty and hinder the high-supported children's ability to make decisive choices or understand the task fully.

Moreover, when placing cards on the projected images of dolls, the children exhibited confusion over the feedback received, particularly when actions on one side (left) seemed to influence their judgments disproportionately. This suggests that the spatial dynamics of interaction with the projection were not intuitively grasped by the children, potentially leading to frustration when their expectations of cause and effect were not met. Lastly, in learning the sequence of dressing, some children with poor cognitive abilities did not recognise the cues provided by numbers indicating the clothing order. This necessitated explicit guidance from researchers, pointing to a gap in the intuitive understanding of the task's sequential nature. The reliance on researcher intervention to convey task objectives emphasises the need for more intuitive design cues that children can naturally interpret to facilitate autonomous learning and reduce frustration.

5.2. Qualitative feedback from therapists

5.2.1. The attractiveness of tangible desktop interaction to autistic children

Therapists' feedbacks highlight the interactive devices' novelty and undeniable attraction, particularly for younger autistic children. One therapist remarked on the project's novelty, T1, stating, *"My personal feeling is that the novelty of this project is perfect, and its attractiveness is beyond doubt"*. This appeal is especially significant for children aged three to five, who exhibit a pronounced interest in animation-like content despite potentially shorter attention spans. This interest is attributed to the novelty and engaging nature of the content, which these children might not frequently encounter in their daily lives. She said, *"I feel that most of these young children are a bit younger, mainly*

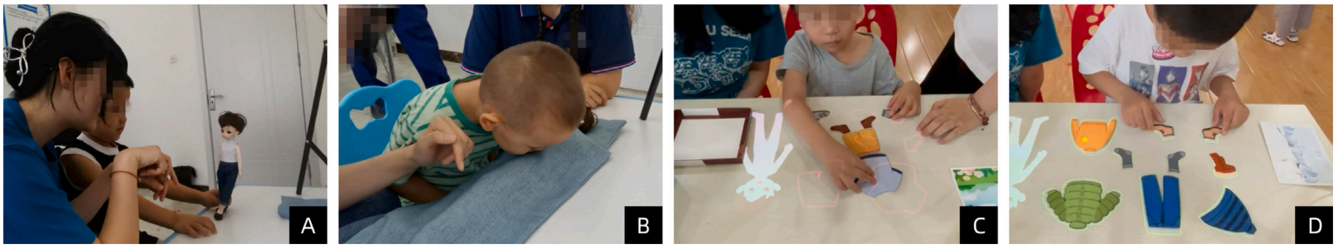

Fig. 8. Exploring sensory and exploratory learning through tangible props: (A) P1 touched the doll and tried to talk to it. (B) P4 kissed the mini quilt. (C) P14 actively picked up cards and tried to match them before officially starting the task. (D) P15 was very careful in aligning these cards with the frames on the projection.

between three and five, so their attention span might be weaker. But they seem very interested in this kind of animation-like content, probably finding it novel and very interesting, and they probably encounter this type of device less often in their daily lives". Another therapist underscored the devices as beneficial tools, particularly for children fascinated by light and shadow, suggesting they derive immense joy from these aspects. Video observations support this, indicating that even children initially fearful or reluctant to engage are swiftly attracted and become active participants upon the system's activation.

Furthermore, T1 emphasised that the children's primary need extends beyond task completion, focusing more on pursuing the device's bright light effects and positive feedback. She mentioned, *"If two matching pieces are put together, and the light immediately comes on, they feel a sense of achievement, that they have done it right... Their inner sense of achievement is happy. The light effects displayed by the system show praise for the children, and this is their need point... I feel that their sense of satisfaction is quite obvious"*. These interactive devices naturally facilitate learning by integrating educational content within the gameplay, markedly increasing the children's learning interest and participation level. This method not only addresses the sensory preferences of autistic children but also meets their educational and motivational needs, rendering the learning experience both enjoyable and effective.

5.2.2. Supplementing the shortcomings of traditional training

Therapists have provided insights highlighting the potential of new technologies in special education, particularly how augmented reality technology can address the limitations of traditional teaching methods. T4 pointed out that although the teaching materials and aids currently used are carefully designed, they sometimes fail to meet each child's specific needs. She stated, *"The teaching materials and aids we use now have been designed, but sometimes they are hard to match each child's situation"*. This comment underscores the challenges of traditional teaching resources in delivering personalised education. She further proposed augmented reality devices as an effective supplement, offering richer and more interactive learning content. For instance, regarding teaching children about visiting a hospital for medical treatment, T4 believes that traditional methods can only narrate the process and lack the provision of actual experience: *"We can only talk about the process, and it is challenging to physically take the children to the hospital to experience the entire process firsthand"*. However, augmented reality devices can significantly enhance this learning by enabling children to engage in repeated demonstrations and drills, thereby acquiring more practical knowledge. She added, *"I believe these augmented reality devices can enrich the learning experience, allowing children to engage in repeated demonstrations and training to gain more practical knowledge"*. This suggests that augmented reality technology offers a more personalised and interactive learning experience and is an effective educational supplement in areas where traditional teaching falls short, such as providing real-life experiences and practical skill training.

5.2.3. Suggestions for future system design

First, the therapist emphasised the importance of repeated demonstrations when introducing new tasks. T1 pointed out that when trying unfamiliar objects for the first time, autistic children prefer having someone demonstrate or guide them and feel more relaxed with their parents' encouragement. This suggests that future system designs should incorporate more demonstration and guidance elements to reduce children's resistance to learning. *"I hope to encourage them to imitate after the demonstration. They can understand that a teacher has just shown this process step by step, which may improve their learning outcomes"*. This highlights the significance of imitation learning and positive feedback in the educational process. Secondly, the therapist recommends individualised graded instruction based on the child's age, abilities, and learning preferences. The insights from T3 and T1 highlight the necessity of creating a flexible system that can adjust to children's varying needs, including initiating pair learning and adjusting the tasks according to the children's progress. T3 asserts, *"When planning new knowledge learning, we start with grading...it should select objectives according to his age, ability level, and special interests"*. This indicates that system design should prioritise personalisation and adaptability to cater to the distinct needs of different children. Lastly, the therapist views the interactive device as a comprehensive system and suggests expanding the teaching content and variety to encompass a broader spectrum of daily life knowledge and skills. T4 stated, *"I believe this interactive system should be integrated with teaching methods to form a methodology for learning daily life skills"*. Moreover, the therapist stressed the importance of employing vivid and intuitive language in the learning process, as well as the critical role of immediate feedback and habitual cues in fostering children's self-confidence.

6. Discussion and design implications

6.1. Enhancing autism interventions with interactive technologies

Integrating interactive technologies into autism treatment settings demonstrates the potential for digital tools to enhance interventions. Developing and implementing advanced desktop applications are crucial for creating scalable interactive environments where children on the autism spectrum can learn and practice daily living skills using tangible tools and storytelling. This system provides sensory enrichment of real-life scenarios combined with enhanced audio and visual effects, improving learning outcomes and reducing the need for intensive interventional training, an aspect that may sometimes be limited in traditional therapy approaches.

This study evaluated autistic children's progress and learning efficiency in completing bed-making and dressing tasks using a staged learning model comprising the learning stage (LS), verification stage (VS), and practical operation stage (PV). Results demonstrated significantly reduced verbal and gestural cues required as children advanced through the stages. Notably, there were statistically significant improvements between LS1 and subsequent stages (LS2, VS, and PV). These results suggest that a step-by-step approach can support children in progressively mastering tasks, thereby promoting greater autonomy and self-efficacy.

However, we acknowledge the alternative interpretation, while the initial reduction in intervention rates indicates progress, the stabilisation of intervention rates in later stages could suggest that children require a consistent level of support to consolidate their learning. We also encourage future researchers to consider the necessity of this factor in investigating whether the observed plateaus represent the generalisation and practice of skills or reflect inherent limitations in the current system's adaptability to individual learning needs.

6.2. Integrating AR and tangible interactions for engagements

The study also explored using enhanced tabletop systems to support autistic children's learning and engagement. Video classification and coding analysis demonstrated that children responded positively to the system, showing significant interest and engagement with the story content. Storytelling was found to capture children's attention and stimulate their observational and expressive skills. For instance, children could learn and complete tasks independently through storylines (e.g., completing the action of covering a quilt), highlighting the effectiveness of storytelling combined with AR in fostering independent learning. Additionally, as visual rewards, animations and sound effects successfully captured children's attention and elicited positive emotional responses, enhancing their motivation to learn. These findings underscore the critical role of positive feedback in AR systems.

Interactions with tangible props revealed significant interest among autistic children in sensory engagement and exploratory learning processes. Learning through direct interaction with physical objects can effectively promote participation and exploratory learning, particularly for children on the autism spectrum. This emphasises the importance of tangible interaction in fostering engagement. Teaching methods integrating AR technology with storytelling, animations, sound effects, and tangible props can provide a more engaging and meaningful learning experience, especially for children with specialised interests. These findings offer valuable insights for further research into the use of AR in children's education, highlighting the importance of multi-sensory stimulation and interactive teaching tools in promoting engagement and learning.

6.3. Design implications for therapeutic practices for autism

Designing therapeutic systems tailored for autistic children is critical to enhancing their development and integration into society (Sartorato et al., 2017). Insights gathered from therapists in this study underscore the importance of such designs, pointing towards the potential for these systems to serve as a foundation for future research in therapeutic practices. By emphasising a personalised, inclusive design process, structured and adaptive learning strategies, comprehensive curriculum development, and enhanced engagement through specialised feedback, therapeutic practices for autism can be significantly optimised. The following design implications should be considered:

6.3.1. Personalised and inclusive design process

The findings highlight that autistic children exhibit diverse preferences and needs due to their varying abilities, such as a fascination with animations, lighting effects, and tangible props. These sensory-driven preferences suggest the need to design systems that prioritise engagement through multisensory experiences while taking into account the specific interests and behavioural tendencies of the target group. For example, children who exhibited tactile engagement with lighting effects or props demonstrated that personalised visual stimulation enhanced their motivation to interact and learn. Therapists emphasised the value of adapting the system to individual needs, such as tailoring tasks to children's age, abilities, and unique preferences. For instance, AR technology can dynamically adjust task difficulty or provide immediate feedback to match the user's cognitive and emotional state. This adaptability ensures that children feel both challenged and supported, creating a learning environment that fosters autonomy and reduces frustration. Additionally, inclusive design elements, such as integrated demonstrations and parent-assisted encouragement, can help alleviate anxiety and resistance to new tasks. Therapist feedback also highlighted the system's ability to address the shortcomings of traditional teaching methods, particularly in creating a safe, controlled environment for practising real-world scenarios (e.g., visiting a hospital or crossing an intersection).

6.3.2. Structured and adaptive learning strategies

The staged learning model employed in the study – comprising learning, verification, and practical operation phases – proved effective for teaching daily living skills through structured and adaptive learning strategies. By gradually introducing tasks and allowing for repeated practice, children internalised steps for activities like bed-making and dressing. The decrease in verbal and gestural prompts across stages illustrates how structured approaches can enhance autonomy and self-efficacy, which are key for long-term development. Furthermore, integrating AR storytelling and feedback mechanisms was crucial for maintaining autistic children's engagement. The narrative context facilitated immersive learning experiences, such as interpreting cues to guide actions. For instance, participants who responded to cues like "night falling" by covering a doll demonstrated how structured storytelling can seamlessly blend instruction with reinforcement. This method supports cognitive development and enhances observational and expressive skills, as children actively interact with story elements and verbalise their observations.

Therapists emphasised the significance of repetitive demonstrations and imitation in helping children understand new concepts, highlighting the need for structured guidance in the early stages. Adaptive systems can progressively reduce external assistance as children advance, fostering independent problem-solving. For example, children who began aligning cards or naming clothing items without researcher input exemplify the potential for adaptive feedback to transition learners from guided to autonomous stages. These findings indicate that structured learning models and adaptive feedback can markedly enhance task performance and learning outcomes. Such systems should feature progressive task difficulty, multimodal feedback (audio, visual, and tactile), and repeated practice opportunities to reinforce learning.

6.4. Limitations and future work

Several limitations to this study must be acknowledged. Firstly, the study was conducted with a relatively small sample size and focused on a narrow age range of young children. This limitation restricts our ability to determine whether the observed effects of the intervention are applicable across a broader age spectrum of children. Secondly, our study did not incorporate a long-term follow-up phase due to privacy and safety considerations for children. This omission prevents a comprehensive comparison of our intervention with traditional therapist-led or teacher-led programs. It limits our understanding of the sustainability and evolution of the skills acquired through the intervention over time. Thirdly, the study did not include a structured process for parents to verify the application of learned skills in home environments. Without this verification, it remains uncertain whether the skills practised within the context of our project effectively translate to real-life settings. Additionally, while the study involved children with diverse diagnoses and support needs, it did not analyse potential differences in how participants with varying support levels responded to the intervention. Autism exists on a spectrum with highly individualised characteristics and needs. This lack of personalised analysis limits our understanding of the varying impacts of the proposed approach.

To address these limitations and enhance the applicability of our findings, future studies will aim to include a more extensive and diverse sample of children, encompassing a wider age range and varying levels of support needs. This expansion will enable a more comprehensive examination of the intervention's effectiveness across different developmental stages and individual profiles, providing a stronger basis for generalisation. Recognising the importance of assessing the long-term impact of our intervention, future research will incorporate follow-up evaluations, comparing the sustained effectiveness of our approach with traditional interventions. These evaluations will provide valuable insights into the durability of the acquired skills. Furthermore, future projects will involve parents in structured processes to verify skill generalisation at home, offering a more holistic view of the intervention's effectiveness in transitioning skills from the training environment to daily life. Lastly, personalisation will be a key focus in future system designs, incorporating adaptive features such as customisable feedback, tailored task guidance, and flexible difficulty levels to better address the unique needs of individuals on the autism spectrum.

7. Conclusion

This research investigates the potential of augmented tabletop interactions to enhance the acquisition of daily living skills among autistic children. Conducted through a pilot study at an autism rehabilitation facility, we gathered data through therapist interviews and observations of the children's behavioural responses. This approach helped establish the design principles and interaction methods for our prototype. Our objective was to assess how AR could improve the learning experiences of autistic children in mastering daily life skills. The system's effectiveness was validated via user studies with 17 children across two institutions, revealing notable enhancements in participant engagement and skill mastery. These results highlight the promise of AR as a support tool for autism treatment through children's task completion, children's behavioural responses, and positive feedback from therapists.

Comparative insights from therapists expanded the study's depth, examining the contrasts between our system and conventional therapeutic approaches and providing feedback on the system's recommendations. By prioritising the specific needs and preferences of autistic children, our work contributes to a deeper comprehension of technology accessibility. Despite its contributions, the study acknowledges limitations such as a small sample size and a brief intervention period. Future research should aim to overcome these limitations, examining the sustained impacts of AR interventions and their applicability across a broader spectrum of skills and settings. Our findings offer valuable perspectives on the use of accessible technologies and the creation of inclusive environments. We aspire to motivate future research in developing innovative technology-based interventions for autistic children to enhance their well-being throughout the learning journey.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical approval granted by the Peking University Biomedical Ethics Committee (IRB00001052-20005), China.

Declaration of Generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used ChatGPT4.0 to grammar check and English polish. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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CRediT authorship contribution statement

Qin Wu: Writing – original draft, Supervision, Methodology, Conceptualization. **Wenlu Wang:** Project administration, Visualization, Validation, Resources, Investigation. **Qianru Liu:** Visualization, Validation, Resources, Investigation, Formal analysis. **Rong Zhang:** Investigation, Funding acquisition. **Yun Suen Pai:** Writing – review & editing. **Mark Billinghurst:** Writing – review & editing. **Suranga Nanayakkara:** Writing – review & editing.

Declaration of competing interest

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

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Data availability

The authors do not have permission to share data.

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