Bridging Climbing and Interactive Smart Spaces for Children

ELEONORA BONELLI*, Politecnico di Milano, Italy
MATTEO SECCO*, Politecnico di Milano, Italy
MATTIA GIANOTTI*†, KTH Royal Institute of Technology, Sweden
DAVIDE DI MARCO, Politecnico di Milano, Italy
FRANCA GARZOTTO, Università di Milano Bicocca, Italy and Politecnico di Milano, Italy
ALESSANDRO COLOMBO, Politecnico di Milano, Italy

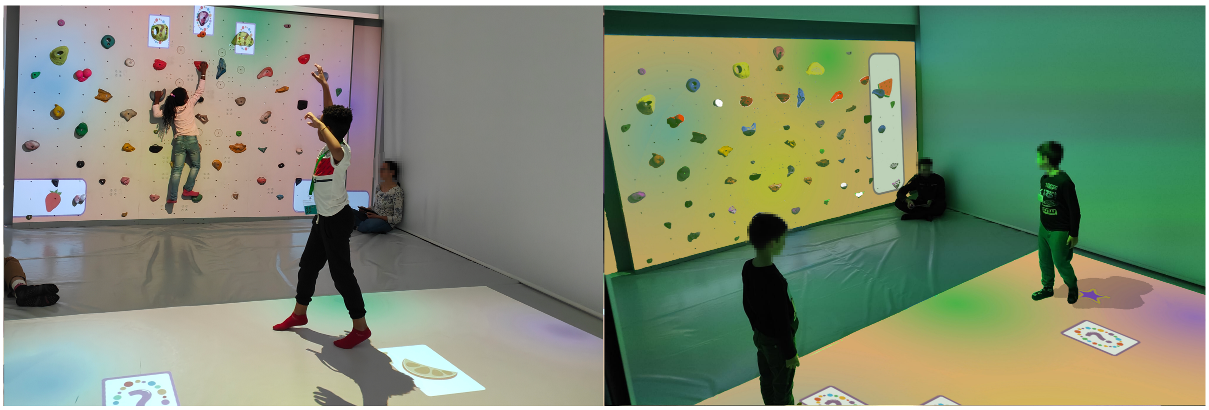

Fig. 1. Children playing in the climbing-augmented interactive smart space during the empirical study

Interactive Smart Spaces (ISSs)-digitally enhanced physical environments that respond to users' movements and gestures with multisensory stimuli-have been proposed as promising platforms to enhance children's social and cognitive skills. However, most existing approaches have focused on low-intensity physical activities. Evidence from exergame research and studies in medicine, psychology, neuroscience, and sports sciences suggests that incorporating medium-to-high physical activity can further improve cognitive and social outcomes.

This paper investigates how such physical intensity can be integrated into ISSs to potentially enhance user engagement, social interaction, and inclusion. We introduce a novel approach that extends traditional ISS interactions with Augmented

*Authors contributed equally to the paper.
†Previously affiliated with Politecnico di Milano.

Authors' Contact Information: Eleonora Bonelli, Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Lombardy, Italy, eleonora.bonelli@polimi.it; Matteo Secco, Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Lombardy, Italy, matteo.secco@polimi.it; Mattia Gianotti, KTH Royal Institute of Technology, Stockholm, Svealand, Sweden, mattiagi@kth.se; Davide Di Marco, Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Lombardy, Italy, davide.dimarco@polimi.it; Franca Garzotto, Università di Milano Bicocca, Department of Psychology, Milano, Lombardy, Italy and Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Lombardy, Italy, franca.garzotto@unimib.it; Alessandro Colombo, Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, Milano, Italy, alessandro.colombo@polimi.it.

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Climbing, where a climbing wall serves as a large interactive surface, with sensorized handholds and footholds acting as interaction affordances. Climbing was chosen for its established physical, cognitive, and social benefits. We present the enabling technologies, describe an interactive game experience designed for primary school children (both typically developing and atypically developing), and discuss the co-design process and strategies to support accessibility and inclusion. Finally, we report on two empirical studies (N = 12 and N = 113), whose findings indicate that integrating Augmented Climbing increases perceived task difficulty but also enhances verbal communication between players-an indicator of deeper social engagement.

The physical and technological infrastructure of ISSs, when integrated with Augmented Climbing, serves as a flexible research tool for exploring a wide range of child-experience research topics and for advancing our understanding of how interactive experiences that combine multisensory stimuli and interactions with varying levels of physical intensity can support cognitive development, social interaction, and inclusion.

CCS Concepts: • **Human-centered computing → Empirical studies in HCI**; **Interaction devices**; *Mixed / augmented reality*; *Collaborative interaction*.

Additional Key Words and Phrases: Interactive Smart Space, Sensorized Climbing Wall, Augmented Climbing, Children, Cooperative Play

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1 INTRODUCTION

1.1 Research Context

Interactive Smart Spaces (ISSs) are physical environments equipped with sensors and actuators capable of perceiving users' movements, gestures, and positions, and responding in real time with a rich variety of multisensory stimuli—such as dynamic floor and wall projections, immersive soundscapes, and adaptive lighting effects.

Our research focuses on child-oriented ISSs, with particular emphasis on game-based, multi-user interactive activities designed to enhance social and cognitive skills—hereinafter referred to as *cognitive-social experiences.* To achieve goals or make progress, these activities involve cooperation and the execution of cognitive tasks, i.e., tasks that require mental effort and higher-order thinking skills, such as attention, memory, problem-solving, and decision-making. Cognitive-social experiences in ISSs have been developed for a variety of purposes, and studies highlight their benefits in domains ranging from cognitive skills promotion (e.g., memory and problem-solving [21]), supporting curricular learning [19, 20], fostering socialization [47] and inclusion [1, 17], and complementing cognitive rehabilitation practices [54].

Research indicates that engaging children in cognitive-social experiences within ISSs—where full-body interaction and multisensory stimuli are central—fosters physical and sensory engagement, which in turn improves retention, motivation, and learning outcomes. These findings are consistent with embodied cognition theories [16, 39, 58–60], which argue that thinking and learning are deeply rooted in the body's sensorimotor experiences and its interactions with physical and social environments. They are also supported by multidisciplinary evidence from medicine, psychology, neuroscience, and sports sciences, showing that age-appropriate physical activity enhances not only children's physical health and well-being but also brain plasticity, cognition, and social development [24].

1.2 Research Gap and Challenges

Existing cognitive-social experiences in ISSs typically involve motor actions of relatively low physical intensity. Body involvement is often limited to moving to and standing at specific points in the space— typically indicated by floor projections—or performing (mid-air) gestures to point, select, or move digital items projected on the wall. However, research on exergames, which combine physical exercise with digital gameplay, has shown that medium-to-high intensity physical activity benefits not only physical health and well-being but also cognition and, in multiplayer contexts, social interaction [22, 25, 62]. This suggests promising opportunities for a novel type of cognitive-social ISS experiences for children that incorporate medium-to-high physical intensity as a means to enhance cognitive and social outcomes, while simultaneously promoting physical exercise as a valuable additional benefit rather than as the primary objective, as in exergames. This area remains largely unexplored, posing both methodological and technological challenges.

1.2.1 Challenge 1: Design. From a *design perspective*, increasing physical intensity in ISSs while maintaining the goal of cognitive and social skill enhancement can be pursued in several ways, including: making full-body interactions more physically demanding; complementing cognitive tasks with distinct physically challenging tasks; embedding cognitive tasks within physically demanding exercises; or combining these strategies. Compared to low-intensity ISS activities and traditional exergames, all these approaches introduce additional layers of design complexity, arising both from the need to integrate physically demanding tasks with cognitive ones in a smooth and natural way and from the requirement to maintain coherence with the immersive and multisensory capabilities of ISSs. To the best of our knowledge, no empirical studies or theoretical frameworks currently provide design guidelines in this domain. Moreover, it remains unclear to what extent—and under which conditions—increasing physical effort in activities primarily aimed at cognitive and social skill development enhances outcomes or, conversely, detracts from them by diverting cognitive resources toward motor control.

1.2.2 Challenge 2: Accessibility and Inclusion. Increasing physical effort in ISSs raises *accessibility* concerns, as differences in users' physical abilities can limit some individuals' ability to participate fully and equitably in a physically demanding experience. Addressing this challenge requires strategies at the intersection of interaction design and physical/environmental design. Such strategies include providing alternative interaction modalities, ensuring safe and inclusive physical setups (e.g., ramps, embedded safety mats, and sufficient spatial clearance for mobility aids), and incorporating sensory-friendly feedback to accommodate children with sensory sensitivities.

1.2.3 Challenge 3: Children's Experience Research. In much research on innovative interactive technologies for children, an Experience Research (ER) approach is adopted [45]. This approach focuses on understanding and designing for the subjective, emotional, and contextual aspects of interaction with technology, exploring how children perceive, feel, and behave during their technology-mediated experiences. However, adopting an ER approach in ISSs—particularly when enriched with medium- to high-intensity physical interaction—poses specific challenges. Involving children in early design stages (as is common in ER) is difficult because it is challenging to provide design artifacts or prototypes that convey the physical and experiential qualities of the interaction before at least a preliminary technological set-up is available. Additionally, established ER methods for children [43] typically combine mixed techniques such as observational methods (e.g., video recording and behavioral coding) and age-appropriate self-report tools. However, observational data collection through video recording can be problematic in immersive smart spaces due to complex lighting conditions, which may hinder visibility and affect coding reliability, and the current state of the art offers limited guidelines for these contexts.

1.2.4 Challenge 4: Technology. From a technological perspective, ISS experiences involving higher physical demands require extended sensing and control capabilities. Systems must be able to reliably detect a wider range of whole-body movements, movement patterns, and physical parameters (e.g., force, intensity, and duration), even under complex lighting and projection conditions, and possibly across larger interaction areas or multiple execution loci. They may also involve the creation of new digitally enhanced physical objects as play materials or interaction affordances, adding complexity to system design, integration, and maintenance.

1.3 Approach

In our research, the introduction of medium-to-high intensity exercise is achieved through making full-body interactions more physically demanding, using a novel interaction paradigm known as *Augmented Climbing* [26, 27]. In Augmented Climbing the climbing wall is used as a large interactive surface, where handholds and footholds act as interaction affordances that trigger multimedia effects.

The rationale for adopting this approach lies in the inherently physically demanding nature of climbing, along with several additional factors. Climbing provides multiple physical benefits (e.g., improved balance, coordination, and flexibility) as well as cognitive and psychological benefits (e.g., enhanced focus and concentration, stress reduction, and increased self-efficacy and confidence) [18, 38]. Moreover, the growing popularity of sport climbing among children may reduce the learning curve associated with the novel interaction paradigm of Augmented Climbing. Furthermore, the modular arrangement of handholds and footholds on sensorised climbing walls allows easy customization of the interaction space to accommodate users with different physical characteristics, thereby supporting accessibility and inclusion. Finally, climbing is often performed in pairs, with one climber and one partner [18, 64], which naturally facilitates the integration of Augmented Climbing into cognitive-social ISS activities involving two children playing different roles.

Our design and evaluation process followed an *experience research approach* [45], focusing on how children perceive, feel, and socially interact within the ISS enhanced with Augmented Climbing. Although in our research only caregivers (primary school teachers and PE teacher, special educator, climbing instructor, therapists specialized in children's development) were directly involved as active co-designers, the design process included a pilot study (N=12) with children playing in the ISS enhanced with Augmented Climbing. This pilot study provided insights not only into the usability of the socio-cognitive activities but also into UX design features and experiential qualities of the interaction. In both the pilot study and a much wider second study (N=113), we collected and analyzed behavioral and experiential data (e.g., engagement, communication, inclusion) and evaluated subjective and social outcomes beyond pure task performance. Our data gathering methodology was aligned with established approaches to children's experience research in HCI [43], combining observational techniques (e.g., behavioral coding of verbal and non-verbal communication, collaboration, and engagement) and age-appropriate Smileyometer-based questionnaire.

1.4 Contribution

This paper contributes to addressing the design and technological challenges discussed above and offers novel contributions to Human – Computer Interaction (HCI), particularly the fields of interactive smart spaces and inclusive play, and the emerging field of Augmented Climbing.

1.4.1 For the HCI community. We present a multiplayer game that exemplifies how interactive experiences in smart spaces can incorporate physically demanding interaction modalities (Augmented Climbing) to enrich cognitive – social experiences for children involving memory and decision-making, and describe how our co-design process was structured and unfolded over time. This contribution can inspire future UX designers to create new experiences for children in ISSs enhanced with Augmented Climbing, and help them to articulate their design process.

Our main empirical study involved 113 primary school children. To the best of our knowledge, there is no empirical study of this size in either the ISS or the Augmented Climbing field. Our findings show that the motor control and physically demanding tasks involved in climbing (e.g., force exertion, body stretching, coordination, and balance) did not compromise usability, enjoyment, or cognitive and social skill development. Despite climbing increasing perceived task difficulty, it appeared to stimulate richer peer communication and supportive behaviors compared to a similar experience involving low-intensity interactions. These results are not obvious since, in principle, increasing physical and mental effort due to climbing could have diverted cognitive resources from social interaction. The main study included 14 children with atypical development playing alongside 99 typically developing peers. The findings indicate no significant differences between these groups, suggesting that combining socio-cognitive tasks with different degrees of physical effort in ISSs may offer promising opportunities for inclusive collaborative games and learning-through-play activities, enabling participation by children with diverse abilities. This study also allowed us to define and validate strategies addressing the accessibility and inclusion challenges in ISSs enhanced with AUgmented Climbing, which lie at the crossroads of interaction design and environmental design. Finally, from an *Experience Research* perspective, we provide methodological insights for combining behavioral coding, linguistic analysis, and subjective experience measures when studying social and cognitive development in physically demanding ISS experiences.

1.4.2 For the Augmented Climbing Community. We show how embedding Augmented Climbing into ISSs extends the focus of Augmented Climbing research beyond physical skill training and individual performance tracking, using climbing as a medium for cooperative, cognitively rich, socially interactive, inclusive, and accessible play for children. Existing research in Augmented Climbing only marginally addresses this user population [28, 40, 41, 51].

1.4.3 For Both Communities (HCI and Augmented Climbing). We provide an example of the physical and techno-logical infrastructure needed to integrate Augmented Climbing into ISSs, which can facilitate the implementation of new interactive experiences in these environments.

2 RELATED WORK

This section offers a concise overview of the ways in which technological advancements have enhanced the climbing experience over recent decades, with a specific focus on Augmented Climbing. Several technological solutions have been developed to support climbing practice, such as wearable devices [4, 31, 33, 36, 46] and sensorized climbing holds [9–11, 15, 30, 37, 52, 53]. Most researchers focus on improving climbing technique through various approaches: displaying target poses to climbers [23, 32, 63], generating computer simulations of climbers solving climbing problems [48, 49], using markerless motion capture combined with neural networks to generate expert pose examples from video recordings [56, 61], or adopting immersive virtual reality [34, 35, 57].

Among the various technological approaches, Augmented Climbing Walls (ACWs) are of particular interest to our work. ACWs are defined as artificial climbing walls integrated with projected graphics and depth camera body tracking to create interactive games and other training applications [26, 27]. ACW approaches have focused on offering diverse and engaging climbing challenges, thereby fostering motivation in indoor climbing, addressing the constant need for new climbing routes, and the difficulty climbers face in identifying specific routes when many are overlaid in a limited space.

Our work draws inspiration from these valuable contributions, but with several significant differences. First, careful attention is given to immersiveness through more extensive visual projections (also on the floor) and auditory feedback in the whole space. Moreover, while prior research has focused on the physical and athletic dimensions of climbing, we mainly adddress its socio-cognitive aspects, with a particular attention to social engagement - an aspect that been identified by climbers themselves as 1 of the 5 primary motivations for climbing [5].

Another key difference is that almost all previous research focused on adult users. Even if the use of ACWs with children has been advocated as it could be particularly well-suited to their enjoyment [27], a limited number of studies have focused on this population [28, 40, 41, 51]. Among these, one study [40] focuses on very young children (9 – 24 months old), whose physical abilities are not yet comparable to those of older children who engage in climbing activities on a climbing wall. To our knowledge, Digiwall [41] remains the only example of a climbing wall specifically designed for children. Using light-enhanced climbing holds, the system blends climbing and gaming experiences, but it does not seek to establish a fully immersive setting (i.e., through visual projection).

3 INTEGRATING AUGMENTED CLIMBING IN ISSs: SET-UP AND TECHNOLOGY

We define *Climbing-Augmented ISS* (CAISS) as an ISS that includes an ACW (Augmented Climbing Wall) and integrates Augmented Climbing with typical ISS interaction paradigms (i.e., movements on the floor and mid-air gestures).

The CAISS developed for the purpose of our research is installed in a dedicated room at one of our university campuses. The size of the physical space is 3.5 meters (height) x 5 meters (width) x 5 (length). The physical set-up is shown in Figs. 2 and 4, and schematized in Figs. 3 and 5. The multimedia stimuli are similar to the one described in [17] and consist of a projection on the wall (A) generated by the frontal projector, a projection on the floor (B) generated by a zenithal projector), smart lights (C), ambient sound (generated by sound system (D)), and soap bubbles that fall from the ceiling (generated by bubble maker (E)). Differently from [17], to detect the user position and movement of the floor we use a body tracking system that receives input from 4 RGB cameras placed on the ceiling (F).

The climbing wall (G) is 3.6 meters (width) x 2.4 meters (height). The wall is equipped with 57 holds, 15 of which are sensorized. The sensorized holds allow children to interact through climbing. They are equipped with triaxial force sensors hidden within the wall and invisible to the user, which measure the magnitude and direction of forces applied to each hold. The placement of sensors and the shapes and dimensions of the holds were determined in collaboration with a climbing instructor to create multiple paths of various difficulties, appropriate for children aged 5-10, and maximize the coverage of the sensorized holds across the paths. Hold placements are spaced 18 cm vertically and 23 cm horizontally. These measures were optimized according to the average anthropometric measures of children aged 5-10.

At the bottom of the climbing wall, there is a 2.5m x 4m safety mattress. Both the wall and the mattress comply with the EN 12572-2 standard. A large, ceiling-mounted retractable curtain is used to hide the climbing wall when the activities involve ISS features only. The curtain can be easily moved up and down, allowing for flexible rearrangement of the space as needed. When lowered, the curtain provides a vertical surface for projection and mid-air gesture interaction that hides the climbing wall (Fig. 2 and Fig. 3). When raised (Fig. 4 and Fig. 5), it opens the space up, creating an integrated space for activities that combine augmented climbing with other interactions in the ISS. The technological setup also includes a tablet for caregivers to activate a game, set the desired configuration parameters (e.g., difficulty level), and control game behavior during play (e.g., stop-suspend-restart a game).

Most examples of body tracking in ISS are based on Kinect [12–14, 17, 19], which is however known to be unreliable when the user is not facing the camera, as in the case of climbing [27]. We, therefore, relied on a custom-made body tracking technology based on Mediapipe [3, 42], which we knew from previous experiences to be reliable in tracking climbing children. 4 RGB cameras positioned on the corners of the room's ceiling. Then Mediapipe extracts the 2d skeletons of children, which are fused into a 3d reconstruction by a modified implementation of the formulas proposed in [7].

The system's software architecture relies heavily on Web Of Things (WoT) technology. The smart lights and the smart plug operating the bubble machine connect to a local WiFi network and can be controlled through the vendor's APIs. The holds of the smart climbing wall are wired on a CAN bus in a daisy chain network. A Raspberry Pi4 on the same bus stores the measures for later analysis and communicates the measurement from the holds to clients in the WiFi LAN registered to its push-based API. A PC, located behind the climbing wall, runs the software to communicate with these APIs, the body-tracking algorithm, and the game applications. A game application receives the data from the sensor controllers (of the sensorized climbing wall and the body tracking), applies the game logic rules, determines the proper multimedia feedback, and communicates with the distributed appliances that actuate the stimuli in the smart environment.

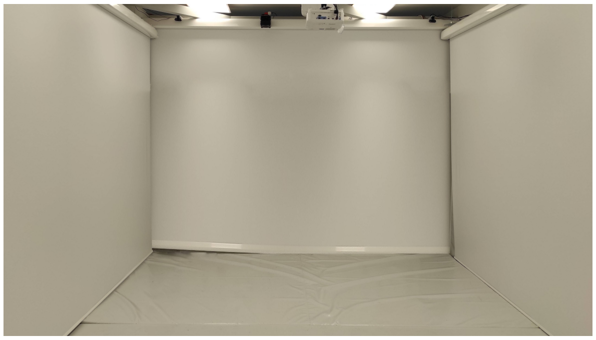

Fig. 2. Physical setup of our CAISS without projections; the Augmented Climbing wall is hidden behind the curtain.

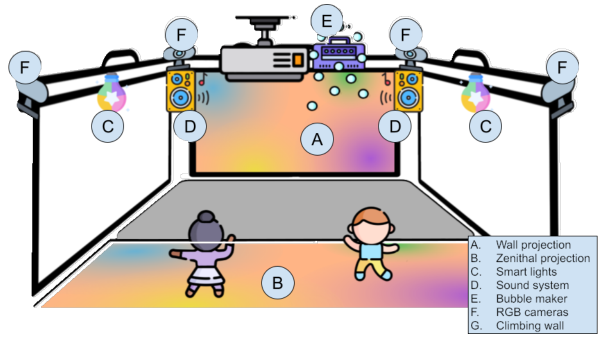

Fig. 3. Structure of the CAISS's sensing and actuation components distributed in the physical space, hiding the Augmented Climbing Wall.

Fig. 4. Physical setup of our CAISS (without projections) showing the Augmented Climbing Wall.

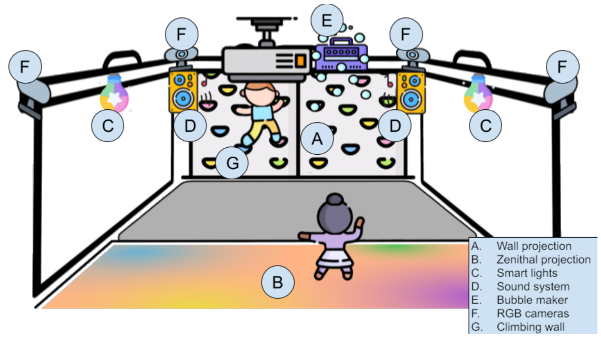

Fig. 5. Structure of the CAISS's sensing and actuation components distributed in the physical space - with the Augmented Climbing Wall.

4 CLIMBING-AUGMENTED ISS: USER EXPERIENCE DESIGN

This section describes an example of a cooperative game for primary school children that we have created in our CAISS.

4.1 Co-design Process

The UX design process engaged a large multidisciplinary team composed of the development group −1 UX designer, 1 visual designer, 4 engineers specialized in ISS, and 2 engineers specialized in sensor networks and data analysis− and a set of domain experts −3 primary school teachers, 1 special educator, 1 PE teacher, 1 climbing instructor, and 6 therapists specialized in children's development. The collaborative journey was structured around 4 main activities, comprising workshops and a pilot empirical study with children. Following each activity, the development team assimilated and refined the contributions of codesign partners, translating them into actionable design specifications and technology requirements, ensuring a feedback loop that informed subsequent design and development stages, showcased in the succeeding activity.

4.1.1 Activity 1: Knowledge Sharing and Requirements Elicitation. The initial workshop sought to establish a shared understanding among the multidisciplinary design team, generate inspiration from both the development team and domain experts, identify user needs, and provide solid requirements for UX design. When we started the codesign activity, we had 2 separate technological set-ups - an ISS and a sensorized, not interactive, climbing

wall - developed in 2 previous projects and installed in different research labs at our university campus.
During the workshop, the development team demonstrated several games available in the ISS and the interaction affordances of the sensorized wall. We then conducted structured brainstorming sessions to share and discuss the goals, motivations, and practices of domain experts, such as multiuser physical exercises and cognitive games for children used in learning, therapy, or body training in classrooms, school gyms, climbing gyms, and therapeutic centers.
Outcome: This activity established a shared overall design vision and defined the core UX requirements, which were translated into initial game concepts serving as starting points for subsequent scenario-based design.

4.1.2 Activity 2: Scenario-based Design. During the second workshop, we first discussed the game concepts from the previous workshop. After converging on one specific activity we delved deeper into its UX design using scenario-based design techniques [6]. Each alternative UX design solution was analyzed and revised in light of technological feasibility and the physical and spatial constraints of the climbing wall and the entire space.
Moreover, accessibility considerations were discussed to enable children with motor, cognitive, or sensory impairments to fully participate in the activities.
Outcome: This activity produced a set of game storyboards illustrating children's interactions (gestures and movements on the floor and the wall) and the multisensory feedback generated in response to these actions (projections, sound, soap bubble generation) as well as final rewards at the end of the game. We also detailed the specifications for the *accessibility requirements*. For the inclusion of children with motor impairments, we decided to replace the room access with a wheelchair ramp, embed the safety mattress into the floor (instead of placing it on top) to facilitate wheelchair movement, and defined an interaction mode that only used ground-reachable holds. To make the game appropriate for children with sensory sensitivities, we ensured that it did not involve any blinking lights and used only calm, soothing audiovisual effects. For children with cognitive impairments, we defined a set of simplified, cognitively less demanding game configurations.

4.1.3 Activity 3: Iterative Evaluation. After the technological development of the system discussed in Sec. 3 was completed and the Climbing Augmented ISS was installed in the final venue, we iteratively showcased progressive prototypes of the activity to domain experts to gather feedback and proposals for UX design improvement.
Outcome: Expert feedback led to refinements in climbing hold positioning, adjustment of multimedia feedback shapes and timing, and improved safety and usability features for both climbers and ground-level participants.

4.1.4 Activity 4: Pilot study. The pilot study (described in Sec. 4.3) involved 12 children. Its goal was to detect potential usability issues, assess the age-appropriateness of our design choices, elicit feedback for UX design improvements, and determine methodological and organizational requirements for the large empirical study planned at the end of the design and implementation stage.
Outcome: The pilot confirmed basic usability but also revealed the need for clearer instructional guidance, a reduced number of sub-tasks within the activity, and more consistent audio and visual feedback. It also informed adjustments to data collection logistics. Details on this activity and its outcomes are reported in Section 4.3.

4.1.5 Activity 5: Final UX and Main Empirical Study Design . The final workshop was devoted to elaborating the pilot study results on the needs for UX design adjustments and to designing the final empirical study.
Outcome: This activity generated the final specifications for UX improvements and produced a detailed experimental protocol for the large-scale empirical study, including group formation criteria, time scheduling for group alternation, data gathering tools (e.g., observation sheets, video recordings, and Smileyometer-based questionnaires), and procedures for session setup and participant flow. These outputs ensured alignment between research objectives, system capabilities, and execution procedures.

4.2 The Children's Experience

The game draws inspiration from Memory, a classic card game particularly popular among children and widely used in educational and cognitive rehabilitation settings.

In Memory, players must find matching pairs of cards by flipping them over and recalling their positions on the board. This game concept was inspirational for several reasons. Memory is known for challenging and enhancing players' memory and concentration skills. Additionally, when played by multiple participants who take turns in card flipping, Memory fosters social interaction. Furthermore, the simplicity of the game materials and rules makes the play experience easy to understand and adaptable to various skill levels, thereby reducing the learning curve and promoting inclusivity. However, classical Memory does not involve full-body physical exercise, presenting a significant challenge in translating the game concept from a board-based activity to a cooperative play experience involving movements and multimedia stimuli on the floor and the climbing wall.

To master the complexity of the UX design, we proceeded incrementally. We first designed a game for the ISS *without* the ACW and then extended the design to include the user interaction with the ACW. The two designs are hereinafter referred to as *MEM* and *MEM** respectively.

The game goal (discovering matching cards) is the same in the two versions. Additionally, both MEM and MEM* involve 2 players, and each pair of children plays 2 turns. In the first turn, one child plays as the *Guide*, and the other child plays as the *Memorizer*. The Guide is responsible for flipping over the first card, while the Memorizer must discover the matching card and flip it over. After all pairs of cards have been matched the turn ends, and the children switch roles, starting the experience with a different set of cards. The game is completed when the second turn is over.

4.2.1 *The Children's Experience in MEM.*

All cards are projected on the floor, while background images are projected onto both the floor and the wall to create a more pervasive experience (See Figs. 6 and 7). The 2 players play in adjacent areas of the floor, divided by a straight line, with the Guide's cards projected on the left side of the floor and the Memorizer's cards on the right side. Cards are randomly arranged in a grid pattern for each play area measuring 3x2 meters.

When the game starts, all cards initially appear face-down. The Memorizer and the Guide use the same action to flip cards over: they must move onto the card and stand on it for at least 3 seconds. To enhance engagement, a small golden star always appears on the floor near the child's feet and follows them as they move. In addition, an "interaction progress bar" is projected near the card on which the child is standing, indicating the remaining time they must stay still before the card flips over.

If the image of the card flipped over by the Memorizer matches the one of the Guide, a cheering sound is played, and green light effects are activated as a reward. The 2 cards then disappear, and the game continues. If the cards do not match, the ambient lights turn red, and the card flips back face down. When the turn is completed, i.e., all pairs have been matched, a victory fanfare is played and a cascade of soap bubbles falls from the ceiling.

4.2.2 *The Children's Experience in MEM*.*

In MEM*, the game logic, the Guide's interaction mode, and the multimedia feedback triggered by the selection of a card are identical to those in MEM. The primary differences lie in the projection of the Guide's cards across the entire floor and, most notably, in the Memorizer's locus of interaction — the climbing wall, where their cards are projected — and the physical actions required for selecting the cards.

The Memorizer's cards are projected onto the wall in a grid pattern measuring 3.6 x 2.4 meters, with each card aligned to a corresponding climbing hold. To flip a card over, the Memorizer pulls the associated hold (which is placed at a different height to allow children unable to climb to still participate in the activity) for at least 3 seconds. A pulling force of at least 2kgf is required to complete the action. A progress bar, displayed as a green ring around the hold, indicates the remaining time for the pulling action.

Fig. 6. MEM set-up during the pilot study.

Fig. 7. MEM* set-up during the pilot study.

4.3 Pilot Study

The goal of the pilot study was threefold: i) to gather children's feedback on the likeability and usability of the experience, particularly concerning the interactions on the wall and the appropriate placement of the holds (reaching the cards had to be neither too difficult for children who have never climbed, nor too simple for children with previous climbing experience); ii) to detect UX weaknesses and elicit hints for design improvement; iii) to identify methodological, organizational, and logistics requirements for the final empirical study.

4.3.1 Participants and Procedure. The pilot study involved 12 children aged 7-9 ($\mu = 7.58, \sigma = 0.79$), 11 typical and 1 atypical, and their parents, recruited among families known by the codesign team. The children were grouped in pairs. Each pair received an explanation about the game and played MEM* once, switching roles as required by the game rules. While 2 children were playing, the other children and adults watched them. The codesign team observed children during play, taking notes about critical aspects of interaction. At the end of the experience, each child filled out a UES-SF questionnaire [50] and answered extra questions inquiring if they had previous experience with sport climbing and how much (on a 1-5 scale) they liked playing MEM*.

4.3.2 Results. Usability and likeability scores were very high (UES-SF Score: $\mu = 4.27, \sigma = 0.38$). We tested the correlation of the children's climbing experience with the perceived usability of the activity. Results showed a Pearson correlation of 0.16, which is negligible. Even if the sample size is small and the result is not statistically significant, this finding suggests that MEM* activity was usable and enjoyable by all participants independently from the previous climbing experience. The observations collected by the design team provided many insights into children's behaviors and indicated the need for some UX design changes. The main ones were the following.

1) we had background images projected on the floor and the wall (see Fig. 7 and Fig. 6) to increase the aesthetics and immersivity of the environment. Still, we noticed that these visual effects were distracting, particularly for the Memorizer, and made it more difficult for the child to identify the holds associated with the cards and memorize card positions on the floor.

Therefore we resorted to replacing these images with smoother, color-sprayed ones.

2) we noticed that some children found it hard to understand the card-flipping mechanism. Therefore we included a simple tutorial during which children try the interaction mechanisms using examples of cards projected on the floor and the wall.

3) we observed that some of the youngest children struggled to find matching cards; they had difficulties devising an exploration strategy, and did a lot of trial-and-error, with a break-in phase that could last up to 3 minutes. We reduced the number of card pairs from 6 to 4, and we introduced a warm-up phase at the beginning of each turn when all cards appear uncovered for 5 seconds, then flip over, to give children the opportunity to memorize their position before starting the game

The pilot study was also used to refine specific details of the main study's procedure and experimental protocol (Sec. 5.2). We observed that the presence of other children and adults during the game acted as a distraction. Therefore, for the main study, we decided that only three members of the design team—the study moderator and two observers—would be present during the children's play. Additionally, we organized a dedicated area outside the room for children to relax while waiting for their turn. The UES-SF questionnaire was found to be too long and complex for the children, so we designed a custom questionnaire with fewer questions and simpler language. Finally, we revised the behavioral observation grid to include additional relevant behavioral signals identified as significant by domain experts observing the children during play.

5 MAIN STUDY

Fig. 8. A Memorizer and a Guide discussing which cards to select to complete a match in MEM during the main study

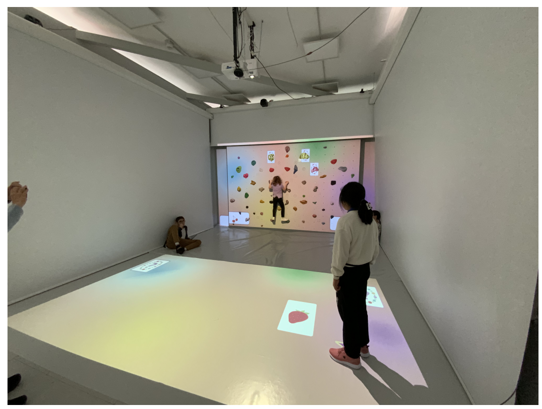

Fig. 9. A Guide observing the Memorizer climbing to reach a card while playing MEM* during the main study.

5.1 Research Questions and Experimental Design

After refining both MEM and MEM* based on the insights from the pilot study, we used them as case studies to explore the effects of enhancing the physical intensity of a cognitive-social activity in an ISS by introducing the Augmented Climbing interaction mode. In line with the rationale for our research discussed in the "Introduction" section and the experience-research nature of our approach (see "Related Work"), the final study focused on how children perceive, feel, and socially interact, addressing two main research questions: *RQ1) "How do children perceive and experience the introduction of a physically demanding interaction modality (Augmented Climbing) within a cognitive-social activity in an ISS?"* and *RQ2) "In what ways does Augmented Climbing influence children's social interaction, collaboration, and engagement compared to the same activity with standard low-intensity interactions?"*. To address these questions, we designed a within-subjects controlled study comparing the two-player cognitive-social activity *MEM* (control condition), which involves only low-intensity ground-based motor actions for both players, with MEM* (experimental condition), which preserves the same game logic, multisensory effects for success and failure, and the same interaction mode for one player (the Guide) but introduces a physically demanding interaction mode for the other player (the Memorizer), namely climbing actions on the sensorized wall. For each research question, we identified multiple research variables and corresponding data-gathering methods, as detailed in Table 1.

Table 1. Schematic overview of the research questions investigated in the final empirical study, the associated variables, and the data collection methods used for their measurement.

Research Question	Research Variable	Data Gathering Method
RQ1) How do children perceive and experience the introduction of a physically demanding interaction modality (Augmented Climbing) within a cognitive-social activity in an ISS?	RV1.1) Likeability	Custom Questionnaire
	RV1.2) Task comprehension	Custom Questionnaire
	RV1.3) Ease of task	Custom Questionnaire
	RV1.4) Self-efficacy	Custom Questionnaire
	RV1.5) Cooperation with peer	Custom Questionnaire
RQ2) In what ways does Augmented Climbing influence children's social interaction and engagement compared to the same activity with standard low-intensity ISS interactions?	RV2.1) User engagement	Behavior Observation
	RV2.2) Interaction with peers	Behavior Observation
	RV2.3) Interactions with the adult	Behavior Observation
	RV2.4) Linguistic Production	Video recording
	RV2.5) Conversation Dynamics	Video recording

5.2 Procedure

The main experiment spanned over 3 days. Each day, 2 classes of children from 2 nearby schools reached the university facility to participate in the study, one in the morning and the other in the afternoon. Each class was divided into 4 groups of 4 to 6 children, with a maximum of 2 atypical per group, depending on the severity of the condition. The groups were chosen by the teachers to have children with matching personalities. Teachers did not supervise the groups during the activities, except for the atypical children who had a support teacher. Still, support teachers did not actively participate in the game and were instructed to avoid any interference with the children's behavior. An atypical child played together with a typical child. For atypical children, we adapted the physical and memory tasks according to their specific needs. For example, for children with movement impairments, in MEM*, the cards appeared closer to the ground on the climbing wall. For children with cognitive impairments, we reduced the number of card pairs in both experimental conditions.

Each group had 45 minutes to play in our CAISS, during which children, divided into pairs, were asked to play the 2 activities MEM and MEM* as described in Sec 4.2. Each pair played each activity twice, with children swapping roles. While a pair of children were playing, the rest of the group was involved in stretching and drawing exercises to ensure they did not peek, which would have created a confounding factor. Drawing and stretching were chosen as they allowed us to keep them busy and focussed, without fatiguing them too much. After completing a full turn in MEM or MEM*, each pair of children was asked to fill out a custom questionnaire regarding the activity, which we describe in Sec. 5.4.

To address possible learning effects due to the order in which the activities were played we counterbalanced the order of activities: in the morning children played MEM first, and in the afternoon they played MEM* first.

During each session 1 researcher explained the rules to the children, 1 controlled the functioning of the room's equipment, 2 performed the live behavioral observation (1 for each child), 1 administered the questionnaire, and 1 entertained the non-playing children.

Before the beginning of the study, detailed information about the study, including methods, objectives, and data gathering, was provided to the participants and their families. Consent was obtained after providing this comprehensive information. The experimental protocol received approval from the ethical committees at our university. We adhered to the recommendations of the European Data Protection Supervisor (EDPS) regarding security, privacy, and confidentiality.

5.3 Participants

We recruited a total of 113 children from 1st and 2nd grade classes at 2 local primary schools. 38 participants were in the 1st grade (24 males, 14 females), while 75 were in 2nd grade (44 males, 31 females). All classes had a mix of typical and atypical children, and there were in total 14 atypical children. For privacy reasons, researchers did not have access to the children's exact diagnoses or other sensitive information.

5.4 Data Gathering

The data-gathering methods are described below, while the relation between the data-gathering tools, the corresponding research variables, and the related research questions, are summarized in Tab. 1.

5.4.1 Custom Questionnaire. To investigate RQ1 we created a questionnaire that users could answer with smileometers, using some key questions and symbols reported according to the guidelines of [43]. Research variables RV1.1 to RV1.5 were translated into straightforward questions formulated in an easy language: Q1) "Did you like the game?", Q2) "Did you understand how to play?", Q3) "Was it easy to play this game?", Q4) "Did you feel like you were good at the game?", Q5) "Did you play together with the others?". Scores are based on a 1 to 5 scale, with 1 meaning an absolutely negative response and 5 an absolutely positive response.

5.4.2 Behaviour Observation grid. To investigate RQ2 we modified the observation grid presented in [17], defining a set of 22 behavioral signals which are summarized in Tab. 2. Social behavioral signals were grouped by target (the person towards which the behavior is directed - peer or adults - linking behaviors to RV2.1, RV2.2, and RV2.3). We also classified social behavioral signals as "Positive" and "Negative", to identify prosocial and antisocial behaviors, respectively.

During children's play, two observers (one for the Guide and one for the Memorizer) annotated occurrences of the behavioral signals using a tablet application. This tool facilitated the recording of behaviors, automatically associating each behavioral signal with timestamps and the unique identification number of each child.

5.4.3 Audio and Video Recording Tools. To investigate RQ2 we used the video recordings from the 4 video cameras used for body tracking, placed at the 4 corners of the room's ceiling and the audio from an ambient microphone was placed on the ceiling in the center of the play area, were used for video analysis. Starting from audio recordings, children's verbal production was manually transcribed and time-stamped using the ELAN annotation tool [44] by two researchers, after an initial training phase. Cohen's Kappa statistic [8] was computed to determine the interrater agreement, obtaining a value of 0.83, which shows substantial agreement.

To analyze the Linguistic Production (RV2.4) we defined 4 linguistic measures, computed for each child: L1 (the spoken time of each child); L2 (how many intelligible proper words they uttered); L3 (how many questions they asked), and L4 (how many assertions they made). To operationalize Conversation Dynamics (RV2.5) we consider turn-switches (L5). In conversational analysis [55], the term "turn" indicates a stretch of speech from one speaker during which the other participant assumes the role of listener. Turn-switch measures how frequently the speaking role shifts between participants during a conversation. A high number of turn-switches may indicate active participation and engagement among the speakers.

6 RESULTS

Summarizing what we described above, our study included 2 research conditions, MEM and MEM*, while the population could be split into subpopulations according to scholar grade (first or second), role in the activity (Guide or Memorizer), and developmental profile (typical and atypical). Eleven out of the 113 children were able

Table 2. Summary of all tracked behavioral signals with the observational grid.

	RV2.1) user engagement	RV2.2) interaction with peers	RV2.3) interactions with the adult
Positive	B1) Expresses amusement not verbally, B2) Verbally expresses amusement	B3) Congrats to the peer, B4) Invites peers to participate, B5) Draws the peer's attention to a game element, B6) Positively comments on the experience, B7) Verbally offers help B8) Offers help with gestures, B9) Verbally asks for help, clarification, or repetition, B10) Asks for help, clarification, or repetition with gestures	B11) Follows the instructions, B12) Asks for help, clarification, or repetition, B13) Draws attention to a game element, B14) Positively comments on the experience,
Negative	B15) Expresses dissatisfaction not verbally, B16) Verbally expresses dissatisfaction	B17) Physical or verbal provocative or aggressive behaviours B18) Negatively comments on a peer, B19) Negatively comments on the experience	B20) Expresses some dissatisfaction, B21) Refuses to follow instructions, B22) Negatively comments on the experience

to complete either MEM* or MEM but not both, due to organizational issues. These subjects were excluded from our analysis. Among the 102 remaining children, 10 were atypical and 92 were typical. In the following, we separately report the results on user perception, behavioral analysis, and linguistic analysis.

Statistical analysis was performed using IBM SPSS Statistics (IBM Corp., NY, USA). The level of significance was set at $\alpha = 0.05$. We did not check the normality of data, but when performing repeated-measures ANOVAs, Mauchly's tests verified the sphericity assumption. If the sphericity condition was not met, Greenhouse-Geisser corrections were applied. Notice that sphericity holds with 2-level factors. For statistically significant results, we then computed mean differences (MEM* MEM) using Bonferroni corrections.

To check whether these results are affected by developmental profile (typical or atypical) or scholar grade (only for custom questionnaires), we defined the variable Δ_i^v, $i \in \{1, \dots, 102\}$, $v \in \{Q1, \dots, Q5\}$ for custom questionnaires, $v \in \{B1, \dots, B22\}$ for behavioral signals, and $v \in \{L1, \dots, L4\}$ for linguistic measures, as the score difference between MEM* and MEM for each child i and each variable v. This step was performed separately for the Climber and the Memorizer in case of behavioral signals and linguistic measures. When data normalization was required, this step was performed afterward, in accordance with each specific normalization method. Then, we performed a two-sample t-test to compare the distributions of the Δ_i^v between the subpopulations (typical and atypical, and 1st and 2nd grade for custom questionnaires).When performing two-sample t-tests, Levene's tests verified the equality of variances assumption. If the condition was not met, corrections were applied.

6.1 Children's Perception

All 102 children filled out the custom questionnaire. We first analyze the variation in perception between MEM and MEM* on the whole population, and then we discuss the dependence of the results on developmental profile and scholar grade. The average scores over the whole population for each question are reported in Tab. 3. The repeated-measures ANOVA revealed statistically significant differences for Q2 (F(1,101) = 4.499, p = 0.036) and Q3 (F(1,101) = 4.375, p = 0.039). The mean differences (MEM*-MEM) are $\mu = -0.19$ ($\sigma = 0.09$) for Q2 and $\mu = -0.24$ ($\sigma = 0.11$) for Q3.

Therefore, Q2 and Q3 got higher scores in MEM than MEM*, meaning that children perceived as more difficult to understand and to play MEM* than MEM. The perception of likeability (Q1), self-efficacy (Q4), and cooperation with peers (Q5) were the same in the 2 experimental conditions.

The two-sample t-test found no statistically significant difference between the distributions of Δ_i^{Q2} and Δ_i^{Q3} when comparing the atypical and typical population, nor when comparing first and second graders.
The results are therefore not affected by scholar grade or developmental profile.

Table 3. **Mean** *(std error)* of the custom questionnaire scores on a scale from 1 to 5.

	MEM	MEM*
Q1) Did you like the game?	**4.75** *(0.64)*	**4.83** *(0.51)*
Q2) Did you understand how to play?	**4.60** *(0.68)*	**4.41** *(0.94)*
Q3) Was it easy to play this game?	**4.59** *(0.75)*	**4.35** *(1.07)*
Q4) Did you feel like you were good at the game?	**4.44** *(1.03)*	**4.55** *(0.79)*
Q5) Did you play together with the others?	**4.57** *(0.71)*	**4.53** *(0.81)*

6.2 Behavioural Analysis

Since the task for each role is different, we separately analyze the behavioral signals of Memorizer and Guide. Among the 102 children, 100 played as Memorizers in both MEM* and MEM; 91 played as Guides in both MEM* and MEM. Thus the behavioral analysis of Memorizers and Guides is performed over 100 and 91 children, respectively. For each role, we analyze the variation between MEM and MEM* on the whole population. Then we explore the dependence of the results on children's developmental profile (typical and atypical). The distribution of the behavioral signals is reported in Fig. 10. We classified the behavioral signals as *frequent* if they occur more than 10 times and *sporadic* otherwise.

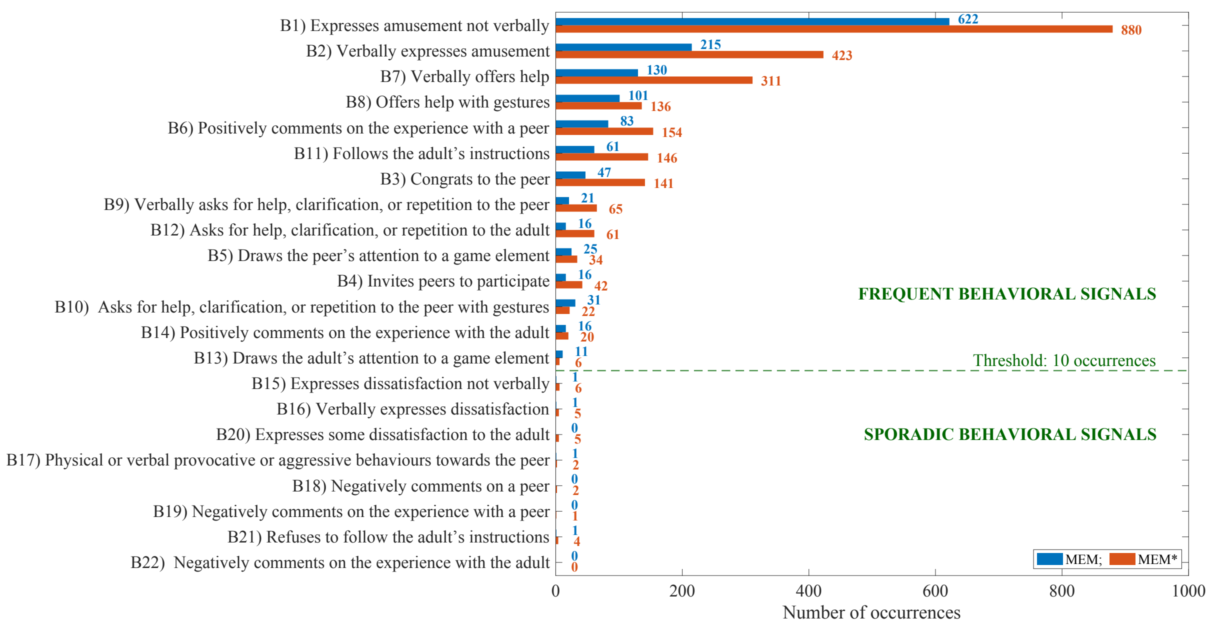

Fig. 10. Occurrences of all behavioral signals recorded during the full experimental study, dividing the frequent behavioral signals from sporadic behavioral signals.

6.2.1 *Sporadic Behavioral Signals.*

Given the limited number of occurrences of sporadic signals, we performed only a qualitative analysis.

Comparing Fig. 10 and Tab. 2, we notice that all the negative behavioral signals are sporadic, and occurred between 0 and 7 times in all 20 hours and 35 minutes of experimental study. Furthermore, no child exhibited more than 2 negative signals in their whole experience (i.e. playing MEM and MEM* in the 2 roles).

Fifteen negative signals out of 24 were observed in the atypical population: 2 atypical children (12% of the atypical population) expressed negative behavioral signals in MEM, and 9 atypical children (69% of the atypical population) in MEM*. Those negative behavioral signals are mainly related to dissatisfaction with the difficulty of the game (B15, B16, B20).

6.2.2 Frequent Behavioral Signals Both in MEM* and MEM, children were allowed to play until the completion of the task, i.e., finding all matching pairs. Task duration was highly variable: the duration statistics for MEM are μ = 126s, σ = 49.5, while the duration statistics for MEM* are μ = 214s, σ = 79.6. Similarly high variability was found in the total number of behavioral signals expressed by each child. Thus, we compared the behavioral signals of each child in the 2 experimental conditions in terms of their *frequency* (number of behavioral signals every 180s) and their *percentage* (number of behavioral signals normalized by the total number of behavioral signals of the same child).

Repeated-measure ANOVAs detected statistically significant differences, for the Memorizer in the frequency of B1 ($F(1,90) = 17.748$, $p < 0.001$), B3 ($F(1,90) = 10.049$, $p = 0.002$), B6 ($F(1,90) = 5.118$, $p = 0.026$), B7 ($F(1,90) = 5.853$, $p = 0.018$), and B11 ($F(1,90) = 5.695$, $p = 0.019$), and in the percentage of B1 ($F(1,99) = 8.857$, $p = 0.004$), B2 ($F(1,99) = 4.328$, $p = 0.040$), B10 ($F(1,99) = 5.636$, $p = 0.006$), B11 ($F(1,99) = 8.302$, $p = 0.005$), and B12 ($F(1,99) = 11.414$, $p = 0.001$); and for the Guide in the frequency of B1 ($F(1,90) = 17.748$, $p < 0.001$), B3 ($F(1,90) = 10.049$, $p = 0.002$), B6 ($F(1,90) = 5.118$, $p = 0.026$), B7 ($F(1,90) = 5.853$, $p = 0.018$), and B11 ($F(1,90) = 5.695$, $p = 0.019$), and in the percentage of B1 ($F(1,90) = 5.388$, $p = 0.023$), B3 ($F(1,90) = 8.051$, $p = 0.006$), and B7 ($F(1,90) = 20.330$, $p < 0.001$).

The results of comparisons for both roles are reported in Tab. 4. In general, most behavioral signals with statistically significant differences in frequency and percentage are characterized by an *increase* of these values in MEM* compared to MEM, although with some differences in the different roles. For the Guide, there is a statistically significant *increase* of both frequency and percentage of congratulations to the peer (B3), an increase in frequency concerning positive comments on the activity (B6), and verbal help offered to the peer (B7). For the Memorizer, there is a statistically significant *increase* in the percentage of verbal expression of pleasure (B2), and in the frequency and percentage of help requests to adults (B12). The behavioral signals characterized by a *decrease* are the percentage and frequency of B1 (for both the Guide and the Memorizer), frequency of B11 for the Guide, and percentage of B12 for the Memorizer.

The two-sample t-test found no statistically significant difference between the typical and atypical subpopulations.

6.2.3 Verbal and Non-verbal Behavioral Signals. Table 4 highlights an interesting pattern. Among the signals that manifest a statistically significant mean difference (MEM*-MEM) in frequency or percentage, all the signals with a strictly positive mean difference (i.e., B2, B3, B6, B7, B12) are relative to verbal communication, while those with a strictly negative mean difference (B1 and B10) are relative to non-verbal behavior. In this subsection, we investigate this phenomenon.

We defined a variable called Verbal Behavioral signals (*VB*) whose count is equal to the union of the occurrences of all signals relative to verbal behavior (namely B2, B3, B4, B5, B6, B7, B9, B12, B13, and B14), and a variable Non-Verbal Behavioral signals (*NVB*) whose count is equal to the union of the occurrences of all signals relative to non-verbal behavior (namely B1, B8, and B10). We left B11 (Follow the instructions) out of this analysis since this behavior can be expressed verbally and non-verbally, and we could not classify it univocally.

The repeated-measures ANOVA detected statistically significant differences, for the Memorizer, in the frequency ($F(1,99) = 5.746$, $p = 0.018$) and percentage ($F(1,99) = 14.961$, $p < 0.001$) of NVB; and, for the Guide, in the frequency

Table 4. **Mean** (*std error*) of the differences (MEM*-MEM) in frequency and percentage of behavioral signals computed using Bonferroni corrections for each role on the entire population. Behavioral signals are reported first individually and then grouped by Verbal Behavioral signals (VB) and Non-Verbal Behavioral signals (NVB). Only statistically significant differences are reported.

	Frequency		Percentage	
	Memorizer	Guide	Memorizer	Guide
B1) Expresses amusement not verbally	–	**-1.495** *(0.333)*	**-0.081** *(0.027)*	**-0.070** *(0.030)*
B2) Verbally expresses amusement	–	–	**0.027** *(0.013)*	–
B3) Congrats to the peer	–	**0.443** *(0.140)*	–	**0.033** *(0.012)*
B6) Positively comments on the experience with the peer	–	**0.042** *(0.018)*	–	
B7) Verbally offers help	–	**0.605** *(0.250)*	–	**0.079** *(0.017)*
B10) Asks for help, clarification, or repetition with gestures to the peer	–	–	**-0.03** *(0.013)*	
B11) Follows the adult's instructions	**0.279** *(0.130)*	**-0.181** *(0.076)*	**0.031** *(0.011)*	
B12) Asks for help, clarification, or repetition to the adult	**0.243** *(0.068)*	–	**0.019** *(0.006)*	–
VB) Verbal Behavioral signals	–	**0.950** *(0.405)*	–	**13.028** *(2.330)*
NVB) Non-Verbal Behavioral signals	**-0.830** *(0.346)*	**-1.728** *(0.426)*	**-10.720** *(2.771)*	**-8.307** *(2.803)*

(F(1,90) = 5.502, p = 0.021) and percentage (F(1,90) = 31.269, p < 0.001) of VB, and in the frequency (F(1,99) = 5.746, p = 0.018) and percentage (F(1,99) = 14.961, p < 0.001) of NVB.

The results of comparisons for both roles are reported in Tab. 4. Notice that VB statistically significantly *increases* in MEM* compared to MEM for the role of the Guide, in terms of both frequency and percentage, while there is a statistically significant *decrease* in NVB in MEM* compared to MEM for both roles, in terms of both frequency and percentage.

The two-sample t-test detected a statistically significant difference between the typical and atypical subpopulations in Δ_i^{VB} for the Guide, computed after normalizing by the total number of behavioral signals of the same child (percentage). This means that the developmental profile does not significantly affect the results of this section, except for the variation of the Guide's Verbal Behavior, when measured as a percentage.

6.3 Linguistics Analysis

Among the 102 children, 21 children were not properly recorded due to technical failure of the microphone. The linguistic analysis is performed over 70 Memorizers and 67 Guides since 11 subjects were not intelligible while playing as the Memorizer and 14 subjects were not intelligible while playing as a Guide.

Due to the highly variable durations of play tasks in MEM and MEM*, L1 was normalized as the percentage over the task duration. L2, L3, L4, and L5 were normalized over the task duration and reported as frequencies of words, sentences or turn-switches per minute. The repeated-measures ANOVA detected statistically significant differences, for the Memorizer, in L1 (F(1,69) = 5.746, p = 0.019), L2 (F(1,69) = 4.416, p = 0.039), and L3 (F(1,69) = 5.777, p = 0.019); and, for the Guide, in L1 (F(1,66) = 18.779, p $<$ 0.001), L2 (F(1,66) = 13.185, p $<$ 0.001), and L4 (F(1,66) = 11.978, p $<$ 0.001). The repeated-measures ANOVA, considering each pair of children as a single statistical unit, detected no statistically significant differences in L5 across the 2 experimental conditions. The results of comparisons for both roles are reported in Tab. 5.

The table highlights statistically significant *increases* in the percentage of spoken time (L1) and frequency of words (L2) for both roles, the frequency of interrogative clauses (L3) for the Memorizer, and the frequency of declarative clauses (L4) for the Guide. The two-sample t-test didn't find any statistically significant difference between typical and atypical children.

7 DISCUSSION

In this section, we discuss the findings of the study focusing on the statistically significant results only.

Table 5. **Mean** (*std error*) of the differences (MEM*-MEM) of linguistic measures computed using Bonferroni corrections for both roles. Only statistically significant differences are reported.

	Memorizer	Guide
L1) Spoken time as percentage of task duration	**0.014** *(0.006)*	**0.030** *(0.007)*
L2) Intelligible proper words uttered per minute	**0.026** *(0.012)*	**0.052** *(0.014)*
L3) Questions asked per minute	**0.002** *(0.001)*	–
L4) Assertions made per minute	–	**0.009** *(0.003)*
L5) Turn-switches per minute	–	–

7.1 RQ1: How do children perceive and experience the introduction of a physically demanding interaction modality (Augmented Climbing) within a cognitive-social activity in an ISS?

The results on children's perceptions emerging from the custom questionnaires show that all questions obtained very high scores (Tab. 3), which indicates a very positive perception of all the investigated aspects in both MEM and MEM*.

The statistically significant reduction in the score of Q2 (RV1.2 - task comprehension) and Q3 (RV1.3 - ease of task) from MEM to MEM* indicates that MEM* was perceived as more difficult to understand and to play. This may be own to the higher physical and cognitive challenges of MEM*: besides involving memory skills, MEM* requires learning how to reach and grab the holds to flip the cards.

Despite this, the scores of Q1 (RV1.1 - likeability), Q4 (RV1.4 - self-efficacy), and Q5 (RV1.5 - cooperation with peers) show no statistically significant difference between the 2 experimental conditions. This suggests that the children did not perceive the addition of augmented climbing as making MEM* less likable, more stressful, or less cooperative than MEM. This was not an obvious result: according to teachers and therapists, most children tend to like less the games that are more physically and cognitively demanding. It may be however explained in terms of the higher engagement contributed by climbing, which may have compensated for the effects of the higher perceived difficulty of MEM*. Successfully completing climbs can boost self-confidence and the belief in one's ability to overcome challenges, thus promoting a sense of self-efficacy.

Perceived collaboration with peers (Q5) does not exhibit any significant difference in the two experimental conditions, while the analysis of linguistic signals suggests an increase of task-related communication in MEM*, which is a form of social behavior according to [2]. Indeed, collaboration with peers was perceived by the children as very high in both activities (Tab. 3), and this may have generated a ceiling effect. Additionally, as suggested by teachers and therapists in our codesign team, children may have not yet developed the capability of discriminating among different forms, and quantities, of social interaction in cooperative experiences that were both so engaging.

Another noteworthy result is that the variation of children's perception between MEM and MEM* in task comprehension (score of Q2) and ease of task (score of Q3) is not significantly affected by developmental profile, as shown by our comparison of the distributions of Δ_i^Q in the populations of typical and atypical children. Homogeneity of distribution between the 2 populations means that we can quite safely attribute our results to children in both populations, even though the typical population had a much larger numerosity than the atypical population.

As a last note, the fact that the distributions of Δ_i^{Q2} and Δ_i^{Q3} between the populations of first-graders and second-graders are not significantly different implies that age was not a relevant factor in limiting the children's ability to understand and play the game. This supports our design hypothesis, that the proposed activity was suited to the population age range.

7.2 RQ2: In what ways does Augmented Climbing influence children's social interaction, collaboration, and engagement compared to the same activity with standard low-intensity interactions?

Results on this question are drawn from the Behavioural and Linguistic analyses.

The analysis of the aggregate verbal (VB) and non-verbal (NVB) behavioral signals shows that the transition from MEM to MEM* pushes the children to increase their use of the verbal communication channels when playing as the Guide and to reduce the use of nonverbal communication in both roles. A rather obvious cause of this may be that, in MEM*, the task of the Memorizer includes climbing on the wall. During this phase, the Memorizer faces the wall and uses both arms and legs to climb. In this condition, verbal communication is the only feasible channel between the Guide and the Memorizer.

The analysis of the individual behavioral signals further details that the increase in verbal communication for the Guide mainly regards expressions of congratulation (B3) and positive comments (B6) to their peer, and verbal help offered to their peer (B7). The analysis of the individual signals of the Memorizer shows that the verbal requests for help directed toward the adults present in the ISS (B12) increase in MEM*, possibly contributing to triggering the larger amount of verbal help offered by the Guide. Using the Interaction Process Analysis terminology [2] the introduction of the interactive climbing experience (MEM*) seems to mainly lead to an increase of both task-related and relationally focused communication.

The remaining significant changes in individual behavioral signals regard the decrease in non-verbal expressions of pleasure (B2) for both Guide and Memorizer and the decrease of non-verbal requests for help directed toward the adults (B10) from the Memorizer. Both effects are consistent with the interpretation that the climbing activity is posing limitations on non-verbal communication, and these are pushing the children towards greater use of verbal communication.

The findings of linguistic analysis are consistent with the above interpretation of the behavioral data. The increase in verbal communication when transitioning from MEM to MEM* predictably causes an increase in total spoken time (L1) and number of words (L2) for both the Guide and the Memorizer. In particular, the declarative clauses (L4) increase for the Guide and the interrogative clauses (L3) increase for the Memorizer. This is consistent with our hypothesis that the increased communication mainly consists of requests for help from the Memorizer (who is climbing) to the Guide, and help instructions from the Guide to the Memorizer. The need to identify the right hold adds a layer of complexity to the game and induces more need for help and therefore more communication. The finding that verbal production (L2) increased in MEM* but the number of turn-switches (L5) did not significantly change between MEM and MEM* may indicate that most verbal interactions in MEM* consisted of longer and more articulate messages, and could be related to the extra effort required for climbing.

Negative behavioral signals were all sporadic, which is of course a positive result, and more frequent among atypical children. The low frequency of negative behavioral signals means that these effects were transitory and of little impact in absolute terms. This was supported by informal comments by the teachers regarding the children's positive behavioral responses to the proposed tasks. The uneven distribution of negative signals between typical and atypical children is in line with the common traits of most developmental conditions in managing difficulties and novelties: in the context of this experiment, children were exposed to a combination of physically intensive exercise and cognitive tasks, in a new environment, and in the presence of strangers.

7.3 Final Remarks

In short, and in the light of our results on RQ1 and RQ2, the activity in the Climbing-Augmented ISS was perceived as more difficult to understand and to play. However, the greater perceived challenge offered by augmented climbing and the nature of the MEM* task (separation of the physical interaction space, climbing challenge) prompts an increase of the so-called task-related social behavior [2] manifested in terms of verbal communication. These findings suggest that the introduction of an high-to-medium intensity physical activity – such as augmented climbing – in the ISS can be designed while fostering, instead of hindering, the socio-cognitive processes, stimulating richer and more articulated verbal communication.

Additionally, in most of the cases, we did not detect any significant difference between the typical and atypical population. Hence,the homogeneity of variations between typical and atypical populations implies that our results equally apply to typical and atypical children. This final observation reveals that our design choices were effective in ensuring the accessibility and inclusivity of the experience. Although preliminary, these findings point to promising opportunities for inclusive collaborative play experiences that thoughtfully integrate physically demanding tasks with less intensive interactive activities within ISSs.

8 LIMITATIONS

Despite the study providing valuable insights into the potential of integrating augmented climbing with ISS, it has some limitations, and the effects of introducing climbing into ISS warrant further validation in larger and longer-term studies.

The primary limitation concerns the short duration of the children's experience: each child participated in only one game session (including role switching) in each experimental condition. We cannot exclude the possibility that the high levels of likability and engagement measured in both MEM and MEM* are partially attributable to novelty and the "wow-effect" [29], which may diminish as children become more familiar with the game and the environment. However, previous studies on ISS [17] have shown that these factors remained relatively stable in longer and repeated sessions. This prolonged effect could also occur when augmented climbing is incorporated into the children's experience due to the versatile nature of climbing. Climbing offers opportunities to experiment with different and novel movements, making the experience continually new, and the challenge of attempting new routes to complete tasks, which is an intrinsic goal that inherently enhances engagement.

We observed an increase in task-oriented social behavior in MEM* compared to MEM. The children had to develop and share problem-solving strategies to address the challenges of the new game, and much of the social behavior observed was focused on providing help and acknowledgment from the child on the floor to the child on the wall. We hypothesize that the effect of climbing on social behavior may persist through multiple sessions, given the inherently open nature of climbing, which encourages children to continually devise and share new strategies to optimize task achievement.

In our study, the typical and atypical subpopulations were unbalanced. We recruited entire classes from local schools, and the prevalence of atypical children in our sample (approximately 9 percent) reflects the proportion of children with atypical development in the general educational system. While this makes the subpopulation sizes representative of real-world situations, it also results in a relatively small sample size for the atypical population, a common limitation in studies involving atypical children. This limits the statistical power for separate analyses of the atypical and typical populations. We mitigated this limitation by performing a repeated-measures ANOVA on the whole population and assessing whether developmental profile influenced the results.

Another limitation, common in studies involving atypical subjects, is the heterogeneity of participants' clinical profiles. This diversity was unavoidable in our study due to the recruitment of subjects from schools with highly diverse populations. In future work, we plan to recruit participants from a large local therapeutic center, with which we collaborate on other projects, that provides specialized treatment to a broad range of atypical children. This will enable us to replicate the study with more homogeneous sets of atypical participants.

Some atypical participants had severe motor impairments that we did address by customizing the game as described in section 5.2 (Procedure). Still, even facilitating the game tasks, the climbing tasks could pose significant challenges for children with even more severe impairments or with certain physical disabilities. Further studies should explore how to remove potential barriers for this population and offer alternatives or stronger forms of adaptation.

Finally, a technical limitation is related to the quality of the children's speech recordings, which was sometimes poor. Since we used an ambient audio recorder, background noise occasionally affected the audio, particularly when children spoke simultaneously. This impacted the completeness of the verbal transcriptions. In future studies, the use of personal radio microphones worn by each child could help mitigate this issue.

9 CONCLUSIONS AND FUTURE WORK

Our work offers several significant contributions, which have been outlined in the Introduction (Sec. 1.4), and it opens up new and promising avenues for future research.

The physical and technological infrastructure of Climbing-Augmented Interactive Smart Spaces (CAISSs) enables the development of a wide variety of physically demanding cognitive-social activities for children and serves as a flexible research tool for investigating a broad range of interaction design and child experience research topics, as well as for addressing research questions and variables beyond those explored in the study reported in this paper. For example, CAISSs support comparisons between gamified climbing experiences on interactive and non-interactive climbing walls, as well as gamified climbing activities enriched with the multisensory and immersive features of ISSs. This represents a valuable direction for future research, offering a deeper understanding of how interactive smart space technologies transform physical play experiences.

Developing and evaluating a broader set of activities would also support the creation of robust guidelines for the design and use of Climbing-Augmented ISSs among children.

Additionally, we aim to deepen our contribution to the field of children's inclusion, building on the promising outcomes of our study involving a mixed population. In collaboration with disability experts we plan to design and empirically evaluate new activities in our CAISS tailored to children with specific cognitive or motor disabilities. Expanding our work in this direction will enable a more targeted investigation of accessibility issues and the potential benefits of CAISS for children's inclusion, focusing on specific user profiles. This, in turn, will inform the development of more specific guidelines for designing and deploying CAISS for users with diverse needs and will lay the groundwork for new personalized learning and cognitive/motor rehabilitation approaches.

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