TACTOPI: Exploring Play with an Inclusive Multisensory Environment for Children with Mixed-Visual Abilities

ANA CRISTINA PIRES, ITI, LARSYS, Instituto Superior Técnico, Universidade de Lisboa, Portugal
LÚCIA ABREU, LASIGE, Faculdade de Ciências, Universidade de Lisboa, Portugal
FILIPA ROCHA, LASIGE, Faculdade de Ciências, Universidade de Lisboa, Portugal
HUGO SIMÃO, LASIGE, Faculdade de Ciências, Universidade de Lisboa, Portugal
JOÃO GUERREIRO, LASIGE, Faculdade de Ciências, Universidade de Lisboa, Portugal
HUGO NICOLAU, ITI, LARSYS, Instituto Superior Técnico, Universidade de Lisboa, Portugal
TIAGO GUERREIRO, LASIGE, Faculdade de Ciências, Universidade de Lisboa, Portugal

Fig. 1. Pairs of children with mixed visual abilities playing with TACTOPI's multisensory elements and interactive tangibles.

Playful robotics engages children in learning through play experiences while simultaneously developing critical thinking, and social, cognitive, and motor skills through play. Such playful experiences are particularly valuable in inclusive education to promote social and inclusive behaviors. We present TACTOPI, an inclusive and playful multisensory environment that leverages tangible interaction and a robot as the main character. We investigate how TACTOPI supports play in 10 dyads of children with mixed visual abilities. Results show that multisensory elements supported children to experience activities as joyful. Storytelling and guided-play added a layer of meaningfulness to the activities, and the robot engaged children in minds-on thinking. TACTOPI afforded children to engage in collaborative social play and facilitated supportive and inclusive behaviours. We contribute with a playful multisensory environment, an analysis of the effect of its components on social, cognitive, and inclusive play, and design considerations for inclusive multisensory environments that prioritize play.

CCS Concepts: • **Human-centered computing** → **Accessibility**.

Manuscript submitted to ACM

Additional Key Words and Phrases: Children, Play, Visual Impairments, STEM, Inclusion, Collaboration, Tangible, Robot

ACM Reference Format:

Ana Cristina Pires, Lúcia Abreu, Filipa Rocha, Hugo Simão, João Guerreiro, Hugo Nicolau, and Tiago Guerreiro. 2023. TACTOPI: Exploring Play with an Inclusive Multisensory Environment for Children with Mixed-Visual Abilities. In *Interaction Design and Children (IDC '23), June 19–23, 2023, Chicago, IL, USA.* ACM, New York, NY, USA, 18 pages. https://doi.org/10.1145/3585088.3589389

1 INTRODUCTION

Play is a powerful tool for learning [29, 60]. Previous research has shown how play supports the development of intelligence, creativity, social skills, and perceptual abilities [20–22, 26]. These benefits led to new approaches – such as playful robots [7, 55] – to engage children in STEM (Science, Technology, Engineering, and Mathematics) activities. Robotic environments strive to promote fun, collaboration, immersion, and imagination through visually appealing backgrounds, characters, actions, and animations. Learning activities tend to be exciting to keep children intrinsically motivated with constant real-time feedback [9]. These playful approaches show promise to engage children in hands-on experiences and real-world applications, helping to overcome the abstractness of science and mathematics [27].

In recent years, research has started to address accessibility issues in the inherently visually demanding robotic environments to include children with visual impairments [33, 49]. However, despite the numerous benefits of play, accessibility research has overlooked its role when designing robotic environments [36, 50, 51] and children with visual impairments have access to less enthusiastic and more cognitively demanding instruments [16, 36, 51]. Proposed approaches tend to prioritize enabling access and minimize the role of play, engagement, and fun in the learning experience of children. We aim to bridge this gap by creating an accessible and playful robotic environment to support social interactions and inclusive behaviors in children with mixed visual abilities.

To explore the possibilities for more engaging, playful, and accessible robotic kits, we developed a playful multisensory environment, TACTOPI, where children can explore an interactive story through multiple multisensory components and interactive tangibles. Interactive tangibles and multisensory elements provide new opportunities for designing robotic experiences that are both playful and accessible. They have the potential to reduce barriers to inclusion and enable children with visual impairments and their sighted peers to play together while developing social coordination skills such as negotiation, problem-solving, and sharing [18, 30, 40]. Our tangible environment houses 3D printed characters and objects with NFC and is composed of a modular world map, a storybook, challenge cards, a robot, a physical helm, a gamepad, and a speaker (Figure 2). This paper reports findings from a user study where 10 mixed visual ability pairs of children (20 participants, aged between 4 - 13 years old) played with TACTOPI, exploring all its elements. Results show the potential of playful robots and interactive objects with multisensory feedback in promoting play, learning, engagement, and inclusive behaviors, by answering three main research questions:

(1) How do TACTOPI multisensory interactive elements support children with mixed visual abilities in learning through play?
(2) What social (e.g., cooperative play) and cognitive (e.g., pretend play) aspects of play do children adopt while interacting with the TACTOPI playful multisensory environment?
(3) How can the TACTOPI playful multisensory environment foster inclusion among children with mixed visual abilities?

The key contributions of this paper are: 1) the design and development of a playful multisensory environment - TACTOPI - that allows children with mixed visual abilities to solve STEM-related activities by controlling a robot; 2) a qualitative analysis of the user study on learning through play, social and cognitive aspects of play, and the inclusive behaviours that TACTOPI afforded; 3) design considerations for playful multisensory environments that contextualize its use within collaborative and inclusive play activities. These contributions are relevant to accessibility researchers and designers of educational technologies, particularly when promoting learning and inclusion. They provide directions for designing systems to support playful learning activities for children with mixed visual abilities.

2 RELATED WORK

We discuss prior research focusing on: 1) Play, and its relation to learning, types of social and cognitive play and technologies to support inclusive play; and 2) Robots and STEM, including accessible robotics environments.

2.1 *Play*

Play is undoubtedly important in humans' lives, but a complex construct to define as it has many forms and many functions [29, 53, 60]. Play can be considered along a spectrum, ranging from free-play to guided-play, and each with different outcomes [60]. For instance, **free-play** with no extrinsic goal could be optimal to develop social competence while guided-play with the adult scaffolding children could leverage learning processes. When play is considered in the context of learning, **guided-play** is the one that has more positive outcomes [25, 60]. In guided-play, the activity is centered around a learning goal [60], which is particularly helpful in school settings [46, 60] but it is the child the one who directs play which potentially increases motivation [10, 60]. Research on **learning through play** [25, 60] suggests that children learn best when they are cognitively active and engaged, when learning experiences are joyful, meaningful and socially interactive, and when learning is guided by a specific goal.

2.1.1 Types of Social and Cognitive Play. Due to the complexity of play and its importance in a child's development, it has been operationalized in socio-cultural and cognitive dimensions [37, 38, 41, 57]. Parten studied the development of **social play** in young children and linked the kinds of play with children's social skills [38]. For instance, she categorized *parallel and cooperative play*. In parallel play, children are next to each other but play on their own while in cooperative play, children play together with a shared goal, coordinating behavior, role-taking, and turn-taking. Piaget connected different types of play with the different stages of children's development - **cognitive play** [41]. Initially, children engage in *physical play* and then start to *play with objects*. After, children start to engage in *symbolic play*, which supports their understanding of abstract concepts (such as counting with objects). In *pretend play*, children make-believe play, actively experimenting with the social and emotional roles of life, imitating what they see around them and how others are behaving. Lastly, *play with rules* is the type of play where children consider the perspective of others, sharing, and turn-taking. After Piaget, Vygotsky [57] was the second major influence on psychological research on play. He reframed play as a social symbolic activity emphasizing that it reflects children's sociocultural norms. In sum, play has functional, representational, and socio-cultural values relevant to children's cognitive development [37, 41, 57].

2.1.2 Technologies to Support Inclusive Play. Playful activities are now pivotal in learning contexts due to the positive effects of play in the development of thinking skills, social and perceptual-motor abilities [20–22], but often neglected in school settings, especially in inclusive classrooms [54]. Accessibility research has been concerned with giving access to children, but the potential role of play in learning processes, and importantly, as a facilitator of inclusive behaviour in children with mixed abilities, has been outlooked [16, 35]. In 2015, Sobel et al., [51] referred to the under-exploration of technologies to support inclusive play and contributed with a set of key facilitators (e.g., adjustability and focus on children's interests and strengths) and barriers (e.g., required effort and inappropriate technology) to inclusive play.

Since then, researchers have started to explore the use of technology to support inclusive play in different contexts. Verver et al., [56] used **augmented toys** with RFID to facilitate play and social interaction between children with mixed visual abilities. The augmented toys caused more parallel play and object exploration but resulted in less cooperative play when compared with non-augmented toys. **Interactive storytelling** has also been used to create playful activities, even though research on inclusive experiences did not specifically approach play. Inclusive approaches often rely on tangibles due to their ability to provide haptic feedback and on robots due to their embodiment. For instance, Inclusive'R'Stories [3] is a multisensory storytelling system that relies on a robot with emotions to support children with mixed visual abilities to co-create stories. In contrast, in In-Visible Island [2], the robot played the role of the storyteller. Cullen and Metatla [17] have also investigated (and co-designed) inclusive multisensory story mapping to support collaborative storytelling activities with mixed visual ability groups. More recently, Metatla et al., [32] co-designed a robot-based game consisting of racing robots, reading tangible maps, and locating objects at school premises with children with mixed visual abilities to support inclusive social play. Their results showed that children with mixed visual abilities had positive inclusive experiences. However, interacting with the robot remained inaccessible for children with visual impairments who needed to rely on their teachers or sighted peers for assistance.

2.2 Robots and STEM

Interacting with robots support the use of technology and engineering, mathematics, science, and physics, and for that reason, it has been targeted as a potential tool to engage children in STEM [27]. Although teamwork and problem-solving, are the most related competencies when interacting with robots, skills such as computational thinking, mathematical, spatial cognition, communication, problem-solving, critical and logical thinking are also stimulated [7, 24, 27, 58]. Robots are attractive, relevant to learn complex concepts, and can trigger children's creativity and social abilities [9, 27, 31].

Most STEM activities with robots rely on **block-based programming environments** that lower the barriers to learning coding and computational thinking concepts. For instance, Blockly [19] uses visual representations of blocks to create (and learn) concepts such as sequences, variables, loops, or conditions. Coding kits extend (or use) such environments to offer more engaging experiences that often rely on tangible components, such as robots (e.g., [4, 15]). For instance, KIBO [8] is a physical kit that relies on wooden blocks to control a robot. Several studies with children in classrooms have shown these kits' ability to promote both learning and high engagement by promoting and supporting playful activities [7]. However, the aforementioned approaches do not consider children with diverse abilities and therefore are often inaccessible to children with disabilities [16].

2.2.1 Accessible Robotics Environments. In the last decade, it has been an effort to increase the accessibility of robotic environments [27, 36], including those for children with visual impairments. As an example, Blocks4All [33], was built as an accessible block-based environment. It provides tangible output, allowing to program the actions of a robot. These efforts provided an accessible alternative to existing tools for keyboard-based or touchscreen interaction.

A frequent approach to robotic environments is to move away from graphical user interfaces and to rely instead on **tangible interfaces**, usually providing auditory feedback. For instance, Pires et al. [44] conducted exploratory studies with educators and children with visual impairments and recommended a set of characteristics for inclusive robot-based programming environments, such as providing different ways to move the robot and more than one output channel as a means to fit different abilities and learning phases. The authors also highlighted the possible benefits of using robots for **spatial training**, by giving the child a tangible output to understand the relationships between their frame of reference and the robots' one, affording children to train spatial cues, allocentric and egocentric perspectives [44]. Accembly [49] used spatial activities with both tangible input and output by using physical blocks to program the movement of a robot, focusing on a home setting where children engaged in spatial activities with their families. Children relied on the robot's multisensory cues (tangibility and auditory feedforward feedback), objects (as targets), and tactile maps to gather relevant sensorial data complete the activities. Their findings suggest that Accembly promoted learning and engagement for children with visual impairments and their sighted parents [49].

These accessible robotics environments include engaging activities, and most of these works refer to children having fun, usually due to the use of robots, or stories. Still, the main scientific contributions are related to providing access to current activities on a functional level, whereas the role of play and its benefits in terms of cognitive and social development, as well as in promoting inclusive experiences, has been overlooked when designing accessible robotic environments, especially for childhood [16, 36].

3 TACTOPI

We designed TACTOPI to explore multisensory and interactive tangibles to engage dyads of children with mixed visual abilities in playful STEM activities with a robot. TACTOPI combines the Latin word *Tactus* and octopus. TACTOPI's design heavily relies on multisensory (tactile, audio, and visual) feedback to engage children with mixed visual abilities in playful activities. TACTOPI was designed to be open and extensible to other purposes. The multisensory environment (Figure 2) includes: (1) 5 challenge cards with high-contrast visuals, braille, tactile cues, and NFC for audio feedback capabilities; (2) a high-contrast storybook augmented with Braille and audio; (3) 3D animal characters; (4) a robotic device with LEDs and various sensors to move; (5) a *magic stone*, which is an NFC reader, and a speaker for audio feedback (6) a helm augmented with inertial sensors for 3D gesture input; and (7) a gamepad with physical buttons. The electronic parts of the system were custom-built using Micro:bit [1] modules.

3.1 Iterative Design Process

We based our initial design decisions for TACTOPI on prior research relevant to inclusive robotic environments, including features such as high-contrast colors and lights, tactile cues, simple illustrations, easy customization and modification, extensible design, and robot's auditory feedforward feedback [1, 14, 32, 44]. Then, we first conducted an **online survey** - due to COVID-19 restrictions - and depicted TACTOPI's functions through videos to identify flaws and opportunities for improvement. It included 19 open questions on TACTOPI's benefits and limitations, its contexts of use, its components, and playfulness. For those who had experience working with blind children, we queried about TACTOPI's suitability, relevance, and accessibility. We recruited experienced researchers in robotics or/and accessibility and special needs educators (SNEs) through social media and direct emails. Fourteen participants answered the survey - including 2 SNEs of children with visual impairments, and 8 with experience working with children with visual impairments. After, we led a **focus group** with 3 SNEs part of the school where we later conducted the study with children. We assessed their opinion on the feasibility of TACTOPI as a learning tool for children with visual impairments and if this playful approach was adequate to facilitate an inclusive and collaborative learning process.

We analyzed the survey answers and audio transcriptions of the focus group through thematic analyses [13]. As a general overview, participants mentioned the interactivity and diversity of the elements and the design to engage and include children with visual impairments in the activities, but too much complexity could be counterproductive. It was unanimous amongst participants that a playful environment was fundamental for children to learn, be involved,

[1]https://microbit.org/

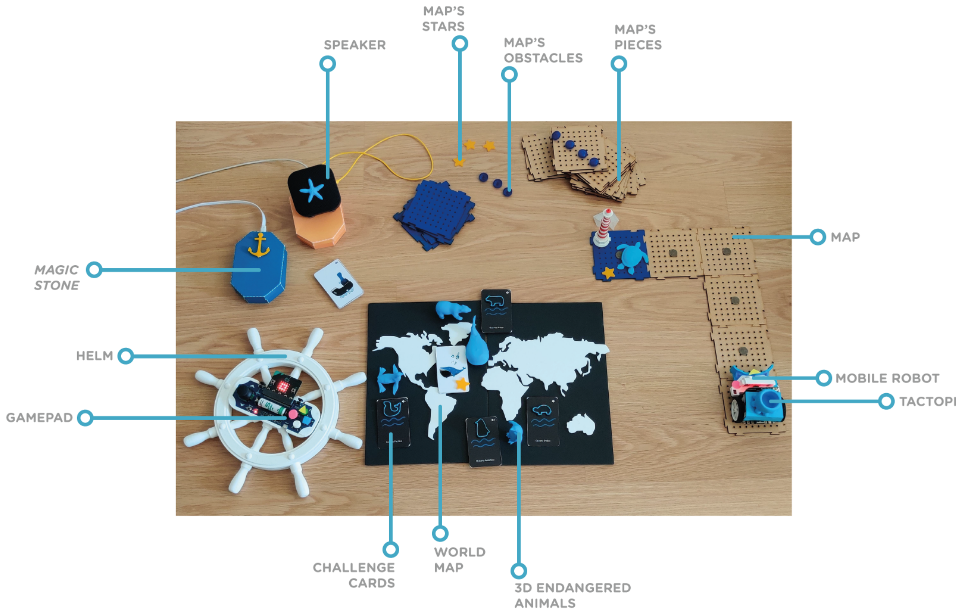

Fig. 2. Overview of TACTOPI.

motivated and creative, e.g.: *"using playful elements collaborates in the greater learning of anyone, not only blind people"*- or *"Playfulness is important to ensure engagement and stimulate creativity."*. The 3D elements and 2D representations were seen as engaging, motivating, and adequate for children with visual impairments to train their mental images of animals. Participants mentioned the robot as a friendly character and the audio as a complementary element for accessibility and joy. This iterative design process allowed us to improve TACTOPI, add a Braille storybook, card labels, increase the buttons' size, and avoid using the world map.

3.2 Playful Multisensory Environment

The environmental maritime missions occur in a playful multisensory environment composed of a story, challenge cards, 3D printed animals, a *magic stone* and the main character (the robot). We leverage a **story** with a relevant and mainstream theme - global warming- as it has been shown that real stories stimulate reflective thinking and facilitate the symbolic representation of learning concepts [14]. The story begins with *tactopi*, a curious octopus that found a magic robot at the bottom of the ocean. With the help of *tactopi* the robot can move, and both start to save endagered animals. We designed five **challenge cards**, each representing a navigational mission within a plot associated with an ocean and an endangered animal. Completing each challenge advances the narrative and presents the next mission. Each card contains an NFC, a relief drawing of the endangered animal, visual contrast to help detect the contours of the elements, and braille [1]. Additionally, children can put the card in the *magic stone*- to listen to the respective challenge. The ***magic stone*** was designed to reproduce the narrative and the auditory feedback of tangibles, cards and robot's movements. It is an NFC reader covered by a blue paper box with a yellow embossed anchor, connected to a speaker with an embossed blue starfish. The **3D-printed animals** also have NFCs to allow children to listen to them by placing

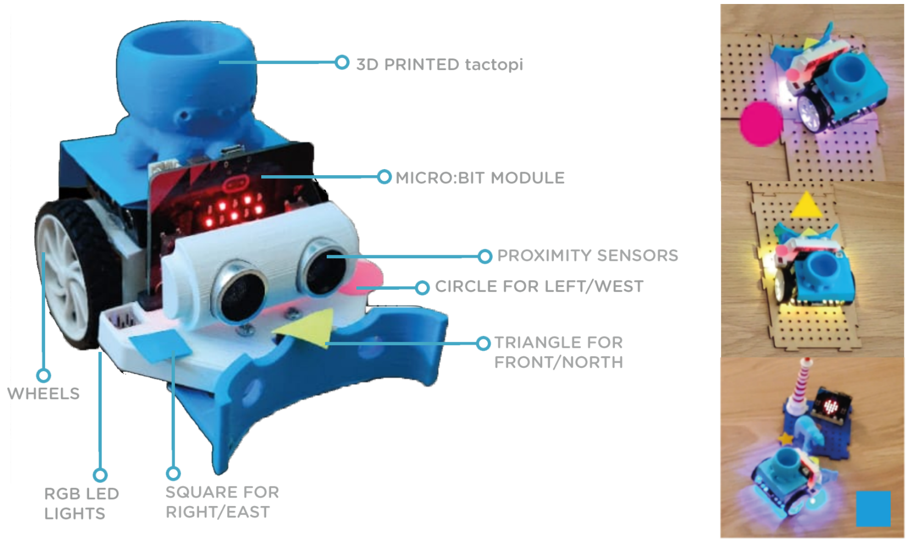

Fig. 3. The robot and its RGB lights for movement.

them in the *magic stone* (Figure 2). We enabled children to record their voices to associate with an animal to encourage personalization, creativity [14, 44] and potentially joy and fun.

The **robot** (Figure 3) is the central element controlled by children and represents a boat with the 3D printed octopus (*tactopi*) on top. It comprises a Micro:bit module for control, movement, LED RGB lights, and proximity sensors. Before the robot starts to move, it speaks out the instruction -feedforward feedback - such as "I am moving forward". When moving, it also projects different colors associated with each direction and brief sounds to help perceive its location on the map, encouraging children to create mental maps of its path [1]. To reinforce laterality concepts, we added unique colored shapes on the robot's sides for each direction that match the gamepad buttons' colors and shapes.

3.3 STEM Activities with the Robot: Coding and Spatial Navigation

We designed two different activities and a compelling plot to promote STEM-related skills. In the **coding activity**, children first identify the mission and then determine the sequence of steps to move the robot using the gamepad buttons (forward, or turn left/right). Then, the robot would verbalize the instructions and start to move accordingly. The robot moves in a tangible map of square cells that can be assembled to create custom paths. The final cell of the map has a solid blue color that stands out in contrast to the rest of the map. The map has a frictionless surface and a central soft circular tactile cue on each cell to allow children to touch and count the number of cells.

In the **spatial navigation activity**, the robot is not restricted to move on a physical map and it is controlled by a 3D-printed helm - an interactive element to control the robot in real-time. The activity supports a sonar functionality; the Micro: bit module emits a continuous melody that increases its *tempo* as the robot gets closer or decreases it if the robot moves away from the target. This type of interaction engages children in spatial navigation activities.

4 USER STUDY

We conducted a user study with ten pairs of children with mixed visual abilities to explore how TACTOPI's multisensory elements and interactive tangibles supported children's play, learning and inclusive behaviors.

4.1 Participants

The study included 20 children aged between 4 and 13 years old ($M = 7.7$, $SD = 2.34$) from an inclusive public school. Educators formed pairs of children by asking children with visual impairments to invite a sighted friend, resulting in:

- *Pair 1* - **C1**, male, 8 years, blind, language and mobility difficulties, and **C2**, male, 7 years, sighted;
- *Pair 2* - **C3**, female, 5 years, low-vision, and **C4**, female, 6 years, sighted;
- *Pair 3* - **C5**, male, 11 years, severe low vision, and **C6**, male, 9 years, sighted;
- *Pair 4* - **C7**, male, 13 years, blind, and **C8**, male, 8 years, sighted;
- *Pair 5* - **C9**, female, 8 years, severe low vision, and **C10**, female, 7 years, sighted ;
- *Pair 6* - **C11**, male, 9 years, blind, and **C12**, male, 6 years, sighted;
- *Pair 7* - **C13**, male, 10 years, moderate low vision, global developmental delay, and **C14**, female, 11 years, sighted;
- *Pair 8* - **C15**, male, 7 years, severe low vision and **C16**, female, 6 years, sighted;
- *Pair 9* - **C17**, male, 4 years, moderate low vision and **C18**, male, 4 years, sighted;
- *Pair 10* - **C19**, female, 8 years, moderate low vision, global developmental delay, attention deficit and hyperactivity disorder, and **C20**, female, 7 years, sighted.

4.2 Procedure

The study took place in a familiar room at a school with the support of SNEs. Children were seated next to each other at a table with all the TACTOPI elements. The study was conducted by three researchers who were responsible for setting up the system and providing guidance and support to the children during the session (Fig. 1).

Children explored and played in an unstructured manner at the beginning of the activity and then we used guided play by scaffolding children towards the specific learning goals [60]. The first two activities served as *ice-breaking* and trust-building between children and researchers and to familiarize them with TACTOPI. The first activity involved children brainstorming around the word "robot", and then children explored the robot turned off. In the second activity, children explored 3D animals, listened to accompanying audio (e.g. "I am the turtle"), and had the opportunity to personalize the audio feedback by recording their own voices and listening to the resulting sound.

Before starting both structured activities, we introduced the narrative and its hero – *tactopi* – by using the story card. Then, children used the challenges cards to introduce each activity mission. Children start by using the turtle challenge card, corresponding to the coding activity, that prompted children to guide the turtle to the jellyfish. We created a map in the shape of a "T" and put a turtle in the center, a plastic bag on one corner, and a jellyfish on the other. The children took turns using a gamepad to control the robot in the direction of the jellyfish (turtle's food). We switched the jellyfish and plastic bag after each turn, and the other child repeated the task.

For the second activity children use the polar bear's challenge card corresponding to the navigational activity. To solve the activity, children listened to the sound of the sonar and one child at a time, would use the helm to drove the robot until it met the polar bear on the melting ice. In the end, we conducted a 5-minute interview with both children to explore their experience with TACTOPI. The whole procedure took, on average, 50 minutes.

4.3 Data Collection and Analysis

We audio and video-recorded all the sessions. Two researchers transcribed the audio and described the most relevant actions observed in the videos. Four researchers coded the transcriptions while watching the videos, using a reflexive thematic analysis (RTA) [12, 13]. We generated initial themes from our theoretical background with a focus on *learning through play* dimensions, and on the social and cognitive aspects of play [37, 38, 41]. We then inductively enriched it with observed codes, such as the observed inclusive behaviors or children's emotional and bodily expressions. To better understand children's behaviors and interactions, we returned to the three SNEs present at the sessions and presented video clips from the study. Our goal was to enrich our analysis by assessing their interpretations as they work daily with these children. These results were also transcribed, triangulated, and analyzed. The same researchers constructed, reflected, discussed, refined the codes, and iterated on the relationships and categorization of the data until achieved a rich interpretation of their meaning and organized them into a consistent story [12, 13, 48, 59]. It is to note that RTA values the researcher's reflective and interpretive engagement with the data, de-emphasizing pursuit of an "accurate" interpretation of the data through reliability measures [12, 13].

5 FINDINGS

We describe the main findings from the qualitative analysis of the user study organized accordingly to our three RQs: learning through play [60], types of social and cognitive play [37, 56] and observed inclusive behaviors. Additionally, we included a last section focused on describing educators' considerations on tangibles for children with visual impairments.

5.1 Learning Through Play

To answer RQ1 **"How do multisensory interactive elements support children with mixed visual abilities in learning through play?"**, we considered evidence on the interplay between learning and play [60]. Learning through play occurs when children's experience is socially interactive, and joyful, with meaning in what they are doing. It allows them to be actively engaged, minds-on thinking and enrolled in an iterative learning process [25, 60].

5.1.1 Experienced as Joyful: the Power of Multisensory Tangibles. We observed joyful interactions with the tangibles and the robot operationalized as the moments where children laughed or explicitly were having fun. Children laughed and made jokes when engaged with the multisensory (visual, audio, and haptic) elements; when constantly listening to the animals' audio (or the ones they created); or by explicitly asking to continue playing, e.g., C3 - *"I want to do it again!"*. The auditory, visual, and tactile properties of 3D objects, cards, and the robot provided children with different means of exploring and engagement, which also triggered their curiosity: *"they liked it and were very curious to understand everything [...] it is interesting that after they grasp and find which animal it was, they wanted to link each animal with its tactile image [on the cards]"* - SNE2.

The audio feedback surprised children the most, facilitating the learning process as children paid high attention to the auditory information. Children were sometimes euphoric, laughing loudly or clapping their hands, especially when listening to the 3D animals' audio and recording and listening to theirs. The possibility to record their voices was much appreciated by the children and gave another layer of enjoyment and playful interaction with the setup. Educators reinforced our observations: *"They loved it! They are extremely sensitive to all that has sounds. Another good thing was to have the animals printed in 3D."*- SNE2.

5.1.2 Meaning in Learning: Narrative, Multisensory Elements, and Guided-Play. The story provided the plot and meaning to engage children in playful activities for commanding the robot toward the goal. The story had a rich narrative to activate children's prior knowledge of marine plastic contamination. Also, we used guided play with researchers and educators scaffolding children to increase meaning-making, making connections between new and old information, aiming to make the new information more meaningful to support learning [60].

Children grabbed the challenge card, put it on the *magic stone*, and listened to the story while making pretend play with the objects by moving, turning, and grabbing them constantly. As a result, children found meaning in the activity that they were doing. For instance, C7 and C8 listened carefully to the bear story, then C8 said out loud with his arms over his head: *"I've heard! [..] he is at risk because it's very hot!"*, C12: *"I realized that the bear is going extinct because of global warming, the temperature is rising, and the ice is melting, and we have to.. with the helm [simulates turning the helm to one side and the other]"*. In another example, after reading the turtle story, we observed children collaborating to decide what the goal of the activity and which trajectory the robot should take: *"[C16] you have to go here to save the turtle"*, C16: *"I understood [. . .] the turtle just wants to eat the jellyfish [and not the plastic bag]"*, C15:*"then take it here to eat this jellyfish"* or after concluding the activity C10 and C11 said: *"I'm glad it did not eat the plastic."*. P4 ended up changing the goal by leading the robot to the plastic bag first, to throw it away, so that the turtle would be safe.

5.1.3 Engaged, Minds-on Thinking and Iterative Learning Processes: Controlling the Robot and Finding Solutions. The robot simulated a boat that had to complete two missions: to help the turtle and to help the bear. These activities allowed children to make sense of the robot, its tactile features, and the multisensory tangibles, keeping them active and minds-on thinking throughout the activities. Children grabbed the robot and the targets (3D animals), counted the cells, and used the robot's perspective to turn in the right direction. They could materialize those abstract concepts, such as directions and the number of cell units, into something real and tangible that they could grab, move, turn and observe the effect of their instructions on the robot's movements. Also, the robot's feedback about its movements facilitated engagement, responding to children's activities with meaningful feedback.

The Coding Activity. It enabled children to apply different computational thinking skills, such as *Problem decomposition* – to break down the activities into a smaller set of instructions. Children started by gathering information needed to solve the activity, engaging in the process of *Data Collection*. For instance, children assessed animal positions, their food, and the robot by locating them on the map, counting how many cells and in which directions should the robot move, or asking their peers for help. At this stage, they would also apply laterality concepts, mental visualization, and perspective-taking. Most of the children autonomously mastered the laterality concepts; however, some needed help to understand how to give instructions by using the gamepad. We coded *Algorithms and Procedures* when the child was able to program a set of instructions by pressing the buttons in the correct order. Frequently, while one child was pressing the buttons and thinking aloud, their peer would help by giving meaningful contributions (explanations, suggestions, and corrections), such as counting how many times does the child need to press and which directions the robot should go, for example, C1 says: *"1,2,3"* and C2 who was with the gamepad, says: *"Forward! (. . .) three times"*. Also, they would iteratively check which instructions were still missing, by counting the map's units, until they had the sequence completed. We also observed *Debugging* behaviors mainly when the robot did not complete the trajectory needed to solve the activity. Children would check the instructions, check if the direction and perspective-taking were correct, and create new solutions.

SNE2 mentioned that using the gamepad *"is more like programming the robot, the other one is just guiding [. . .] I don't think it's easier, but maybe it reminds me more of the games they are used to [. . .] programming also requires memorization* *because you have to see the map units and count how many you need to move to reach the target; they can practice more skills" [...] I notice that C8 and C7 probably play console games home with friends.[...] but often video games are not accessible."*.

We also observed some individual negative reactions when using the gamepad, which did not occur with other TACTOPI elements. We observed explicit boredom behaviors in four dyads, mainly while waiting for their peer to finish completing the sequence with the gamepad. Also, because children have to press the button on the gamepad to start recording the instructions for the robot to move and then press the button to stop recording, two children felt this was boring, and C11 even showed some level of frustration: *"Oh robot stop saying start recording, shut up!"*.

Spatial Navigational Activity. In the helm activity, the *tempo* of the sound gets higher with the robot approaching the bear, supporting also auditory and spatial stimulation. In this activity, children use their spatial navigation skills to update the robot moves in the right direction according to visual and auditory information (or only auditory in the case of blind children). We observed blind children applying an allocentric perspective to move the robot towards the target through auditory localization while peers helped by giving some spatial cues such as "it's almost there". SNE2 mentioned that the spatial navigational activity enables children to work *"the auditory part, [...] realizing that the sound's getting faster [...] gives a little bit of the notion of laterality, but I think the focus is really the auditory feedback and how to adapt the helm's direction."*- and SNE1 added *"auditory and the capacity for attention and concentration [as well]. This requires a great ability to concentrate"*.

We observed children very enthusiastic about this activity. For instance, C3 went after the robot, dancing excitedly, and C10 ran to the bear and spontaneously played by putting the bear inside the robot. C12 mentioned that *"I really enjoyed saving and walking to the bear"*. In general, children preferred using the **helm**, e.g., C8 *"... because it is a helm and you could turn it like this [simulating turning the helm].* In this activity, children did not need to plan a sequence of steps, *[children have just to] rotate [...] that's it, blind children, despite not seeing the robot, guide [it] to the goal as there is the sound component in the background [...] I don't think it's easier but maybe it reminds them more of the games they're used to [...] the other type of activity may be more technical*- SNE2. And SNE3 added: *"maybe [this one] is more stimulating"*.

5.2 Social & Cognitive Play

To answer our RQ2 **"What social and cognitive aspects of play do children adopt while interacting with a playful multisensory environment?"**, we analysed data considering social and cognitive aspects of play [37, 38, 41].

5.2.1 Social Play: Parallel, Cooperative, and Competitive Play. We observed children engaging in three types of social play [38]. **Parallel play**, when children played with TACTOPI elements but did not interact with their peers. Sometimes children were more curious about the sounds and played with the objects individually. This was mainly observed during the initial activities, as children were enthusiastic to understand the tangibles and robots' properties, performing exploratory and manipulative play. We observed children in **cooperative play** more often, by playing with each other, communicating, negotiating ideas, sharing tangibles, and engaging in solving the activities together. In particular, they cooperated to control the robot, by helping each other, negotiating, and facilitating peer discovery.

We also observed **competitive behaviors**, but less often, mostly associated with turn-taking, as children were often impatient to be the first to put the animal on the *magic stone* or the first to use the gamepad or the helm. While this could be seen as negative, SNE2 explains *some are impatient so I think that this type of activity is good to realize that you have to know how to wait. It's a learning experience that they have to do"*. Sometimes a child would grab each of the animals and put it on the *magic stone* to hear it, without letting the other peer intervene. However, in most cases, the other child was also curious and waited to hear the animals' voices and stories, integrated into the activity. One example of a negative interaction: C8 removed the bear from C7's hand (a child with visual impairments) to put it on the *magic stone*. C7 started to negotiate but ended up taking it out of his peer's hand too.

5.2.2 Cognitive Play: Pretend Play and Play with Rules. **Pretend play** allows children to be creative, explore and develop new ideas and roles by transforming various aspects of reality. During pretend play, we observed children coming up with make-believe scenarios and becoming inventive in those scenarios, such as using a helm and exploring roleplay as captains or pretending to have a clash between the robot and the jellyfish and making stories. They often assigned social and emotional actions to the tangibles, for example, they imitated animals' typical sounds or the sound of the animal eating. They were creative, exploring and developing new ideas and roles. In one situation, children engaged in pretend play and changed the target of the activity and the researchers had to include another object in their play: C16 asks *what does the seal eat?* and C15 replies *"the seal needs food!"*. A researcher look around searching for objects in the room and said *"could it be a cake? can the seal eat a cake?"*. C15 said *"is a Nutella cake"* and C16 responded *"ah so the seal will go this way [to eat the cake]"*. We also observed children **play with rules**. Children had to learn and memorize pre-defined rules related to the activities (eg.: goal, procedure towards executing goal), robot operation (eg.: rules associated with commanding the robot), and play in groups (eg.: respect turn-taking, support when needed). They need this type of play to accomplish the expectations and goals of the activity in order to sustain play.

5.3 Increasing Inclusion

To answer RQ3 **"How can a playful multisensory environment foster inclusion among children with mixed visual abilities?"**, we analyzed children's interactions with their peers in terms of inclusive and supporting behaviors.

5.3.1 Supporting peers with visual impairment. We observed inclusive and friendly behaviors between children with mixed visual abilities. Sighted children often gave verbal and non-verbal support to complete the activities' goals.

We observed sighted children assisting children with visual impairments in completing tasks such as finding the path and target locations and assembling a map. The sighted children used gestures such as pointing and guiding their peer's hands to indicate where to go and what to do. They also helped with the use of a gamepad and provided specific instructions. For instance, to count the map pieces: C11- *"no no, it's not two"*, or C15: *"Then you come here with the car [robot], catch the seal and put it here [...] otherwise he will go here"*. Other examples of helping behavior: C15 takes the turtle on top of the robot and puts it next to the jellyfish without using the gamepad to command the robot. C16 corrected his peer and explained that he had to use the gamepad. Then both discussed which would be the button to turn right while C16 indicates where the jellyfish and the robot were. Sighted children would indicate relevant properties of the objects to their peer, such as indicating the tentacles of the octopus, or textures that were associated with directions or explaining some technical components, e.g.: C8 explains that tactopi "is upside down" [on the *magic stone*] and for that reason, they could not listen to its audio, as the NFC was positioned beneath tactopi.

5.3.2 Teaching the sighted peer. We observed that including braille descriptions in the animal and challenge cards resulted in an opportunity to increase inclusion between children with mixed visual abilities. Sometimes sighted children would say with enthusiasm that cards included braille and some would guide the peer with visual impairments hand to the braille location. It was also common to observe that the sighted peer was attentive when the peer read the information in braille, observing their gestures and listening attentively. Children with visual impairments had the opportunity to perceive a cue that the sighted children could not make sense of, a cue that only they mastered; e.g.: C15 taught his peer how to read Braille from left to right with his finger and said *"here is written: tur-tle"*. Including braille could contribute to a more balanced interaction for children with mixed visual abilities.

5.3.3 Using Humour and Opportunity for Bonding. Humor is related to social skills and is a pillar of social bonding. We detected that children used humor frequently as a way to connect with each other and engage in pretend and symbolic play, for eg.: C17 said *"I think the turtle will get a shock [by eating the jellyfish]"* and both children laughed and stared at each other as an intimate moment between them. We also observed that SNEs use humour often with children as it is a powerful tool to learn and strengthen social relationships. To cite one example, C2 had programmed the robot to move forward more than what it needed to and SNE2 said: *"Oh, now try to catch the robot, see where it ended up... it walked, walked, and now where is the robot? [laughs] It disappeared?! It's not even at the bottom of the sea anymore [laughs].*

We observed bonding within some pairs, whispering to each other's ear with affection to say the correct instruction or animal name, or other private comments that were meaningful for them. For instance, in one situation, C8 turns the card over and brings it closer to his colleague, very close to the eyes, and whispers softly: *"it's a bear that is on the ice."*. C8 grabbed C9's hand, they both looked at the camera, and C8 said *"Say hello to the camera!"*, and they both laughed.

5.4 Educator's Considerations on Tangibles for Children with Visual Impairments

Educators mentioned that tangibles could mimic the real object or animal as children are *"young and creating the mental images based on touch"* -SNE2. SNE1 added that this also depends on the type of blindness: *"if it's congenital or acquired [...]. For example, C1 acquired blindness, so it is likely that he has some images already stored in his brain and could recognize more easily what the objects represent [...] possibly, a congenitally blind person does not have this perception because they have never seen a turtle which is something that it's not easy to have available to touch"*.

Educators also suggested using materials that mimic the real-world context, e.g., SNE3: *"supply sand or shells and a tray so children can grab and feel, to give them the sensation of being at the bottom of the sea."*, with the real weight, thermic sensation, textures, and sounds: *"[...] when children touch the materials they could have associated different sounds if it is metal or wood"*. For instance, the *Magic Stone* could be heavy as a real stone and with a similar texture to be perceived as cold. Regarding the audio associated with the tangibles, SNE2 suggested: *At the beginning of each animal's audio, it could play a real animal sound [to] associate the real sound to the animal in 3D."*

Regarding the characteristics of 3D objects, they should have the minimum needed detail. SNE2 explained that: *"a tactile image is an image that isn't too complex. Also, the more details it has, the more complicated would be its perception [...] the real object is always, in my opinion, the best of all, then comes the 3D object and then comes the image"*.

6 DISCUSSION

This study explored the potential of playful multisensory elements to engage children with mixed visual abilities in inclusive activities with a robot. Playful robotic environments are a popular research trend in STEM education [8, 9]. They are attractive constructive learning scenarios for learning complex concepts [8, 9, 33] and engage children in social and collaborative actions [9, 16]. In the context of inclusive education, playful robotics takes even more relevance for promoting playful experiences and strengthening collaboration and social actions among children.

Multisensory Elements in Joy, Meaning, Engagement, Minds-on and in Iterative Learning. Joy is the pillar of playful activities [28], and it primes learning [29]. The interactive tangibles with auditory information triggered children's interest, joy, and attention with the potential to increase intrinsic motivation [28], and support learning and cognition [47, 60]. The tangibility allowed children to perform physical and hands-on experiences, which is known to impact their playful interaction and learning [39, 43], particularly in the context of children with visual impairments [32, 42, 44, 49]. The *audio* and personalization of the animal voices were joyful features leading to children's surprise and curiosity, which is also crucial in play and in learning [11, 52].

The narrative, tangibles, and guided-play supported meaningful learning. Children used the 3D animals to advance the plot providing a sense of purpose to their actions, which has the potential to increase learning outcomes, recall [25], and connect to their prior knowledge [60]. This environment supported children in being creative, adding other objects to the narrative, which contrasts with passive learning with simple memorization – rote learning. We used guided play, or playful learning, to support children to find meaning in the activity, being creative, and to scaffold their exploration, by questioning, and discovering relations to the defined learning goals; but the interaction was child-led. For instance, one pair engaged on their own by modifying the goal of the activity, following their intentions according to the story.

The use of a robot supported children's engagement, minds-on thinking, in an iterative learning process. The robot is an object-to-think-with in the construction of learning [6, 47] and a powerful tool to keep children engaged and on task (high curiosity, active engagement and enjoyment). Having a multisensory robot with auditory output, and as an object-to-think-with [6, 47], engaged children to test hypotheses, experiment functionalities, and create a mental model of coding/spatial navigation. Children were immersed in an iterative learning process of active exploration, discovery, and reflection, by generating and testing hypotheses and updating their understanding constantly.

Multisensory Elements in Social and in Cognitive Play. TACTOPI's multisensory tangibles facilitated cooperative social play. Children used a series of communicative strategies involving negotiating and building on each other's responses, while playfully interacting with tangibles with auditory feedback and braille descriptions. These features allow children to discover together, talk about it, play, and pretend play. Similarly to the study of Verver et al [56], children with mixed visual abilities engaged in solitary play with interactive tangibles when performing exploratory and manipulative play at the beginning of the session. But soon after, children were guided to learning goals and had to cooperate with their peers and use shared resources. Play facilitates children to learn social, functional, and representational values relevant to cognitive development [41]. We observed that tangibles prompted children to pretend to play, actively experimenting, manipulating, and exploring their creativity and functional play. Through make-believe, children experimented with actions, and relationships between 3D animals and the robot. They changed the plot and used humor. We also observed that the robot prompted to play with rules more often. The fact that each pair of children needed to share one robot and one auditory output may have promoted (or forced) sharing, turn-taking, negotiation, and taking the peer's perspective.

Playful Environments Support Inclusion. Playful activities may act as a powerful tool towards inclusion, enhancing affective experiences and strengthening relationships in a more relaxed learning environment [9, 45]. Sighted peers showed inclusive behaviors by supporting the peer with visual impairments by indicating relevant proprieties of TACTOPI or information to solve the activity, which is in line with previous results [34]. Supporting a peer could bring a learning benefit, triggering critical thinking and motivating both children to learn [29, 54]. In an effort to balance the interaction, we added braille in TACTOPI's elements which gave an opportunity to increase communication, curiosity, and knowledge sharing. Children also used humor frequently as a way to connect and while engaging with pretend and symbolic play with tangibles. Humor is a pillar of social bonding [5] important at the social and cognitive levels as it helps to capture the other's attention and to adopt different points of view. Inclusive and multisensory tangible environments like TACTOPI may afford bonding between peers through play, as it gives more room for embodied interaction, facilitates physical proximity, and playful and joyful social experiences. [9, 45].

6.1 Design Considerations for a Playful and Inclusive Learning Environment for Mixed-Visual Abilities

We reflected on our findings and derived design considerations that educators, designers, and developers could consider when creating or a playful inclusive multisensory environment for learning.

Provide Meaningful Narratives and Interactive Tangibles We observed children joyfully engaging in the narrative and connecting the 3D animals to advance in the plot, creating a more meaningful learning context [60]. Apart from it, a narrative can enable children to connect their previous knowledge motivating them to stay on-task [25, 32, 60] while engaging in pretend and cooperative play.

Trigger Surprise and Humor When expectations are violated children engage in the process of "sense-making" or "explanation finding", information-seeking behavior to understand what was violated supporting curiosity and exploration, beneficial in learning [11, 52, 60]. Humor is also very beneficial for learning [5] by promoting positive affect and social bonding, especially in the context of inclusive education, as our findings suggest.

Increase Tangibles' Realism Tangibles give children an opportunity to learn about properties and to create mental representations of real-world objects. Thus, tangibles should mimic real objects with minimum tactile detail [42], to not overload the tactile receptors and impair the understanding of the object. For example, they could mimic the material context, weight, thermic sensation, textures, and sounds.

Provide Multisensory Features but Restrict Audio Output Besides the inherent accessibility of multisensory features, they also have the potential to reduce cognitive load and increase inclusive and playful learning experiences, collaboration, critical thinking, and group discussions [17]. We suggest using shared resources to promote cooperative play and collaboration through sharing, negotiation, and turn-taking.

Balance Interaction for Mixed-ability settings Braille offered blind children with exclusive access to information, which balanced information access, and served as a purpose for communication, teaching, and bonding [54]. To balance the interaction we can involve children's specific knowledge (e.g., braille) or asymmetric interdependent roles [23].

6.2 Limitations

This study explored children's playful interaction with an inclusive multisensory environment in a single session. To minimize the potential novelty effect of one session, we triangulated our observations with children's educators. However, sustained engagement over time remains a challenge that needs further investigation. Another limitation is that children with visual impairments invited sighted friends to play with TACTOPI which could have affected the outcomes compared to unfamiliar peers. However, educators used this strategy to ensure positive experiences. We also acknowledge another limitation in not assessing learning outcomes, despite TACTOPI's success in enabling children to command a robot and apply computational thinking and navigational skills. Future studies should focus on this aspect.

7 CONCLUSION

We present TACTOPI, a multisensory tangible environment that supports children with mixed visual abilities in playful STEM activities. A study with 20 children revealed that TACTOPI promotes play, engagement, joy, and inclusion through interactive elements such as 3D animals and audio feedback. We observed children collaboratively creating hypotheses and testing through exploratory play with tangibles, and using the robot as an object-to-think-with. Although TACTOPI was successful in supporting collaboration, multisensory resources need to be carefully designed to avoid parallel play and support cooperative play. The paper includes recommendations to create inclusive playful scenarios for learning. Further research is needed to measure the long-term impact of TACTOPI on children's learning and collaboration.

ACKNOWLEDGMENTS

This work was supported by national funds through Fundação para a Ciência e a Tecnologia - FCT, Portugal - under the projects UIDB/00408/2020, UIDP/00408/2020, UIDB/50009/2020, and scholarships SFRH/BD/06589/2021 and SFRH/BD/BD/09151/2020, and by the Portuguese Recovery and Resilience Program (PRR), IAPMEI/ANI/FCT under Agenda C645022399-00000057 (eGamesLab).

8 SELECTION AND PARTICIPATION OF CHILDREN

This research study was approved by the Ethics Committee of Faculdade de Ciências (CERPDC, Universidade de Lisboa) and authorized and supervised by School directors and the Special Needs cabinet. We contacted an inclusive public school that has specialized teaching and materials for children with visual impairments. We sent the consent forms to parents/legal tutors with a full description of all activities, analysis and future usage of the collected data. The parents signed the consent form to allow their children to participate in the study. During the study, we asked children if they were willing to participate and all children assented and understood that they could quit anytime. We designed the activities for a positive/playful experience.

REFERENCES

[1] Hatice Ablan and Nilüfer Talu. 2019. Developing Toy Design Criteria for Visually Impaired Children: A New Play Set Design. 7 (03 2019), 36–58.

[2] Ruhiyati Idayu Abu Talib, Predrag K Nikolic, Mohd Shahrizal Sunar, and Rui Prada. 2020. In-visible island: inclusive storytelling platform for visually impaired children. *Mobile Networks and Applications* 25, 3 (2020), 913–924.

[3] Cristiana Antunes, Isabel Neto, Filipa Correia, Ana Paiva, and Hugo Nicolau. 2022. Inclusive'R'Stories: An Inclusive Storytelling Activity with an Emotional Robot. In *Proceedings of the 2022 ACM/IEEE International Conference on Human-Robot Interaction*. 90–100.

[4] Ewelina Bakała, Jorge Visca, Gonzalo Tejera, Andrés Seré, Guillermo Amorin, and Leonel Gómez-Sena. 2019. Designing child-robot interaction with Robotito. In *2019 28th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN)*. IEEE, 1–6.

[5] John A. Banas, Norah Dunbar, Dariela Rodriguez, and Shr-Jie Liu. 2011. A Review of Humor in Educational Settings: Four Decades of Research. *Communication Education* 60, 1 (2011), 115–144. https://doi.org/10.1080/03634523.2010.496867

[6] G.E. Baykal, I. Veryeri Alaca, A.E. Yantaç, and T. Göksun. 2018. A review on complementary natures of tangible user interfaces (TUIs) and early spatial learning. *International Journal of Child-Computer Interaction* 16 (2018), 104–113. https://doi.org/10.1016/j.ijcci.2018.01.003

[7] Marina Umaschi Bers. 2017. *Coding as a Playground*. Routledge. https://doi.org/10.4324/9781315398945

[8] Marina Umaschi Bers. 2018. Coding, playgrounds and literacy in early childhood education: The development of KIBO robotics and ScratchJr. In *2018 IEEE global engineering education conference (EDUCON)*. IEEE, 2094–2102.

[9] Marina Umaschi Bers and Mitchel Resnick. 2015. *The official ScratchJr book: Help your kids learn to code*. No Starch Press.

[10] Pedro J. Blanco, Ryan P. Holliman, and Nicole C. Carroll. 2019. The Effect of Child - Centered Play Therapy on Intrinsic Motivation and Academic Achievement of At-risk Elementary School Students. *Journal of Child and Adolescent Counseling* 5 (9 2019), 205–220. Issue 3. https://doi.org/10.1080/23727810.2019.1671758

[11] Elizabeth Bonawitz, Patrick Shafto, Hyowon Gweon, Noah D Goodman, Elizabeth Spelke, and Laura Schulz. 2011. The double-edged sword of pedagogy: Instruction limits spontaneous exploration and discovery. *Cognition* 120, 3 (2011), 322–330.

[12] Virginia Braun and Victoria Clarke. 2019. Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health* 11, 4, 589–597. https://doi.org/10.1080/2159676X.2019.1628806 arXiv:https://doi.org/10.1080/2159676X.2019.1628806

[13] Virginia Braun, Victoria Clarke, Nikki Hayfield, and Gareth Terry. 2019. Thematic analysis. In *Handbook of Research Methods in Health Social Sciences*, Pranee Liamputtong (Ed.). Springer, Singapore, Chapter 10, 843–860. https://doi.org/10.1007/978-981-10-5251-4_103

[14] Emeline Brule, Gilles Bailly, Anke Brock, Frederic Valentin, Grégoire Denis, and Christophe Jouffrais. 2016. MapSense: Multi-Sensory Interactive Maps for Children Living with Visual Impairments. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems* (San Jose, California, USA) *(CHI '16)*. Association for Computing Machinery, New York, NY, USA, 445–457. https://doi.org/10.1145/2858036.2858375

[15] Kunal Chawla, Megan Chiou, Alfredo Sandes, and Paulo Blikstein. 2013. Dr. Wagon: a'stretchable'toolkit for tangible computer programming. In *Proceedings of the 12th international conference on interaction design and children*. 561–564.

[16] Quentin Chibaudel, Wafa Johal, Bernard Oriola, Marc J-M Macé, Pierre Dillenbourg, Valérie Tartas, and Christophe Jouffrais. 2020. "If You've Gone Straight, Now, You Must Turn Left" - Exploring the Use of a Tangible Interface in a Collaborative Treasure Hunt for People with Visual Impairments. In *The 22nd International ACM SIGACCESS Conference on Computers and Accessibility* (Virtual Event, Greece) *(ASSETS '20)*. Association for Computing Machinery, New York, NY, USA, Article 19, 10 pages. https://doi.org/10.1145/3373625.3417020

[17] Clare Cullen and Oussama Metatla. 2019. Co-designing inclusive multisensory story mapping with children with mixed visual abilities. In *Proceedings of the 18th ACM International Conference on Interaction Design and Children*. 361–373.

[18] Ralph J Erickson. 1985. PLAY CONTRIBUTES TO THE FULL EMOTIONAL DEVELOPMENT OF THE CHILD. *Education* 105 (1985), 261. Issue 3. https://search.ebscohost.com/login.aspx?direct=true&db=a9h&AN=4731911&lang=pt-pt&site=eds-live&scope=site

[19] Neil Fraser. 2015. Ten things we've learned from Blockly. In *2015 IEEE Blocks and Beyond Workshop (Blocks and Beyond)*. IEEE, 49–50.

[20] Doris Fromberg. 1990. Play issues in early childhood education. , 223-243 pages.

[21] Doris Fromberg and Dominic Gullo. 1992. Perspectives on children. , 191-194 pages.

[22] Catherine Garvey. 1990. *Play*. Vol. 27. Harvard University Press.

[23] David Gonçalves, André Rodrigues, Mike L. Richardson, Alexandra A. de Sousa, Michael J. Proulx, and Tiago Guerreiro. 2021. Exploring Asymmetric Roles in Mixed-Ability Gaming. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems* (Yokohama, Japan) *(CHI '21)*. Association for Computing Machinery, New York, NY, USA, Article 114, 14 pages. https://doi.org/10.1145/3411764.3445494

[24] Shuchi Grover. 2020. Designing an Assessment for Introductory Programming Concepts in Middle School Computer Science. In *Proceedings of the 51st ACM Technical Symposium on Computer Science Education* (Portland, OR, USA) *(SIGCSE '20)*. Association for Computing Machinery, New York, NY, USA, 678–684. https://doi.org/10.1145/3328778.3366896

[25] Kathy Hirsh-Pasek, Jennifer M. Zosh, Roberta Michnick Golinkoff, James H. Gray, Michael B. Robb, and Jordy Kaufman. 2015. Putting Education in "Educational" Apps: Lessons From the Science of Learning. *Psychological Science in the Public Interest* 16, 1 (2015), 3–34. https://doi.org/10.1177/1529100615569721 arXiv:https://doi.org/10.1177/1529100615569721 PMID: 25985468.

[26] Johan Huizinga. 2014. *Homo ludens: A study of the play-element in culture*. Routledge.

[27] Myint Swe Khine, Myint Swe Khine, and Ohmer. 2017. *Robotics in STEM Education*. Springer.

[28] Linda Rose Krasnor and Debra J Pepler. 1980. The study of children's play: Some suggested future directions. *New Directions for Child and Adolescent Development* 1980, 9 (1980), 85–95.

[29] Claire Liu, S Lynneth Solis, Hanne Jensen, Emily Hopkins, Dave Neale, Jennifer Zosh, Kathy Hirsh-Pasek, and David Whitebread. 2017. Neuroscience and learning through play: a review of the evidence. *The Lego Foundation, Dinamarca* (2017).

[30] Nancy L. McElwain and Brenda L. Volling. 2005. Preschool children's interactions with friends and older siblings: relationship specificity and joint contributions to problem behavior. *Journal of Family Psychology* 19 (2005), 486–496. Issue 4. https://doi.org/10.1037/0893-3200.19.4.486

[31] Edward F. Melcer and Katherine Isbister. 2018. Bots amp; (Main)Frames: Exploring the Impact of Tangible Blocks and Collaborative Play in an Educational Programming Game. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (Montreal QC, Canada) *(CHI '18)*. Association for Computing Machinery, New York, NY, USA, 1–14. https://doi.org/10.1145/3173574.3173840

[32] Oussama Metatla, Sandra Bardot, Clare Cullen, Marcos Serrano, and Christophe Jouffrais. 2020. Robots for inclusive play: Co-designing an educational game with visually impaired and sighted children. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*. 1–13.

[33] Lauren R Milne and Richard E Ladner. 2018. Blocks4All: Overcoming Accessibility Barriers to Blocks Programming for Children with Visual Impairments. *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems* (2018), 69:1–69:10. https://doi.org/10.1145/3173574.3173643

[34] Jonas Moll and Eva-Lotta Sallnäs Pysander. 2013. A haptic tool for group work on geometrical concepts engaging blind and sighted pupils. *ACM Transactions on Accessible Computing (TACCESS)* 4, 4 (2013), 1–37.

[35] Aboubakar Mountapmbeme and Stephanie Ludi. 2021. How Teachers of the Visually Impaired Compensate with the Absence of Accessible Block-Based Languages. *The 23rd International ACM SIGACCESS Conference on Computers and Accessibility*, 1–10. https://doi.org/10.1145/3441852.3471221

[36] Aboubakar Mountapmbeme, Obianuju Okafor, and Stephanie Ludi. 2022. Addressing Accessibility Barriers in Programming for People with Visual Impairments: A Literature Review. *ACM Transactions on Accessible Computing* 15 (3 2022), 1–26. Issue 1. https://doi.org/10.1145/3507469

[37] Ageliki Nicolopoulou. 1993. Play, cognitive development, and the social world: Piaget, Vygotsky, and beyond. *Human development* 36, 1 (1993), 1–23.

[38] Mildred B Parten. 1932. Social participation among pre-school children. *The Journal of Abnormal and Social Psychology* 27, 3 (1932), 243.

[39] Bjarke Kristian Maigaard Kjær Pedersen, Kamilla Egedal Andersen, Simon Köslich, Fardin Sherzai, Jacob Nielsen, et al. 2018. Towards playful learning and computational thinking—Developing the educational robot BRICKO. In *2018 IEEE Integrated STEM Education Conference (ISEC)*. IEEE, 37–44.

[40] A. D. Pellegrini and Peter K. Smith. 1998. Physical Activity Play: The Nature and Function of a Neglected Aspect of Play. *Child Development* 69 (6 1998), 577–598. Issue 3. https://doi.org/10.1111/j.1467-8624.1998.tb06226.x

[41] Jean Piaget. 45. *Play, dreams and imitation in childhood*. Norton.

[42] Ana Cristina Pires, Ewelina Bakala, Fernando González-Perilli, Gustavo Sansone, Bruno Fleischer, Sebastián Marichal, and Tiago Guerreiro. 2022. Learning maths with a tangible user interface: Lessons learned through participatory design with children with visual impairments and their educators. *International Journal of Child-Computer Interaction* 32 (2022), 100382. https://doi.org/10.1016/j.ijcci.2021.100382

[43] Ana Cristina Pires, Fernando González Perilli, Ewelina Bakała, Bruno Fleisher, Gustavo Sansone, and Sebastián Marichal. 2019. Building blocks of mathematical learning: Virtual and tangible manipulatives lead to different strategies in number composition. In *Frontiers in Education*, Vol. 4. Frontiers Media SA, 81.

[44] Ana Cristina Pires, Filipa Rocha, Antonio José de Barros Neto, Hugo Simão, Hugo Nicolau, and Tiago Guerreiro. 2020. Exploring accessible programming with educators and visually impaired children. In *Proceedings of the Interaction Design and Children Conference*. 148–160.

[45] Sara Price and Paul Marshall. 2013. Designing for learning with tangible technologies. In *Handbook of design in educational technology*. Routledge, 300–312.

[46] Justus J. Randolph, Marjaana Kangas, Heli Ruokamo, and Pirkko Hyvönen. 2016. Creative and playful learning on technology-enriched playgrounds: an international investigation. *Interactive Learning Environments* 24, 3 (2016), 409–422. https://doi.org/10.1080/10494820.2013.860902 arXiv:https://doi.org/10.1080/10494820.2013.860902

[47] Mitchel Resnick. 1997. *Turtles, termites, and traffic jams: Explorations in massively parallel microworlds*. Mit Press.

[48] Kate Roberts, Anthony Dowell, and Jing-Bao Nie. 2019. Attempting rigour and replicability in thematic analysis of qualitative research data; A case study of codebook development. *BMC Medical Research Methodology* 19. https://doi.org/10.1186/s12874-019-0707-y

[49] Filipa Rocha, Ana Cristina Pires, Isabel Neto, Hugo Nicolau, and Tiago Guerreiro. 2021. Accembly at Home: Accessible Spatial Programming for Children with Visual Impairments and Their Families. *Interaction Design and Children*, 100–111. https://doi.org/10.1145/3459990.3460699

[50] PK Smith and A Pellegrini. 2013. Learning Through Play. In *Encyclopedia on Early Childhood Development [online]*, RE Tremblay, M Boivin, and RDeV Peters (Eds.). Springer, Singapore. https://www.child-encyclopedia.com/play/according-experts/learning-through-play

[51] Kiley Sobel, Katie O'Leary, and Julie A Kientz. 2015. Maximizing children's opportunities with inclusive play: Considerations for interactive technology design. In *Proceedings of the 14th International Conference on Interaction Design and Children*. 39–48.

[52] Aimee E Stahl and Lisa Feigenson. 2015. Observing the unexpected enhances infants' learning and exploration. *Science* 348, 6230 (2015), 91–94.

[53] Brian Sutton-Smith. 2009. *The ambiguity of play*. Harvard University Press.

[54] Judith E Terpstra and Ronald Tamura. 2008. Effective social interaction strategies for inclusive settings. *Early Childhood Education Journal* 35, 5 (2008), 405–411.

[55] Julie Torpegaard, Line Søndergaard Knudsen, Morten Præst Linnet, Mikael B. Skov, and Timothy Merritt. 2022. Preschool children's social and playful interactions with a play-facilitating cardboard robot. *International Journal of Child-Computer Interaction* 31 (2022), 100435. https://doi.org/10.1016/j.ijcci.2021.100435

[56] Suzanne H Verver, Mathijs PJ Vervloed, and Bert Steenbergen. 2020. Facilitating play and social interaction between children with visual impairments and sighted peers by means of augmented toys. *Journal of Developmental and Physical Disabilities* 32, 1 (2020), 93–111.

[57] Lev S Vygotsky. 1967. Play and its role in the mental development of the child. *Soviet psychology* 5, 3 (1967), 6–18.

[58] Jeannette M. Wing. 2006. Computational Thinking. *Commun. ACM* 49, 3 (March 2006), 33–35. https://doi.org/10.1145/1118178.1118215

[59] Wen Xu and Katina Zammit. 2020. Applying Thematic Analysis to Education: A Hybrid Approach to Interpreting Data in Practitioner Research. *International Journal of Qualitative Methods* 19, 1609406920918810. https://doi.org/10.1177/1609406920918810 arXiv:https://doi.org/10.1177/1609406920918810

[60] Jennifer M. Zosh, Kathy Hirsh-Pasek, Emily J. Hopkins, Hanne Jensen, Claire Liu, Dave Neale, S. Lynneth Solis, and David Whitebread. 2018. Accessing the Inaccessible: Redefining Play as a Spectrum. *Frontiers in Psychology* 9 (2018). https://doi.org/10.3389/fpsyg.2018.01124