Accembly at Home: Accessible Spatial Programming for Children with Visual Impairments and their Families

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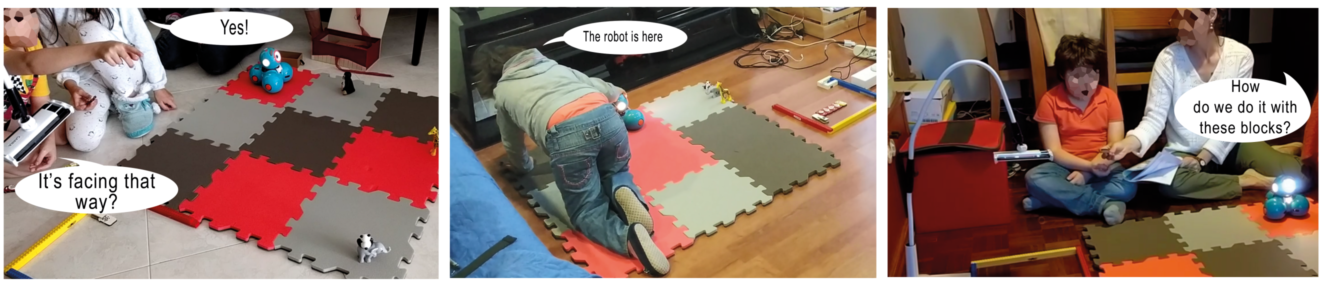

Figure 1: Mixed visual-abilities families using ACCembly. Left: The child confirms with his sibling to where the robot is facing. Middle: Child crawls on the map searching for the robot. Right: Parent scaffold the child in play.

ABSTRACT

Accessible introductory programming environments are scarce, and their study within ecological settings (e.g., at home) is almost non-existent. We present ACCembly, an accessible block-based environment that enables children with visual impairments to perform spatial programming activities. ACCembly allows children to assemble tangible blocks to program a multimodal robot. We evaluated this approach with seven families that used the system autonomously at home. Results showed that both the children and family members learned from what was an inclusive and engaging experience. Children leveraged fundamental computational thinking concepts to solve spatial programming challenges; parents took different roles as mediators, some actively teaching and scaffolding, others learning together with their child. We contribute with an environment that enables children with visual impairments to engage in spatial programming activities, an analysis of parent-child interactions, and reflections on inclusive programming environments within a shared family experience.

CCS CONCEPTS

• **Human-centered computing → Accessibility**.

KEYWORDS

Visually impaired, Children, Computational thinking, Collaboration, Tangible, Robot, Accessible

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1 INTRODUCTION

Computational Thinking (CT) is becoming a fundamental literacy skill, such as reading and writing, and expected to be used worldwide by the middle of the century [49, 68]. CT "is the thought process involved in formulating a problem and expressing it in a way that a computer - human or machine - can effectively carry out" [68]. It borrows concepts from computer science [11], such as sequences, operators, and iteration as well as practices like being incremental and iterative, testing, debugging, abstracting, and reusing. CT's value goes well beyond computing contexts and promises to impact children's social, emotional, and cognitive development [7, 13], while fostering personal and career growth [68]. Block-based programming environments (e.g., Scratch [50] and Blockly [18]) and numerous coding kits have been developed to promote computational thinking in children (e.g., ScratchJr [17], LightBot [73], Cubetto [3], and Coding Awbie [44]). These coding kits open the opportunity for young children to learn CT outside educational settings (e.g., at home).

Existing solutions are visually demanding and inaccessible to children with visual impairments (VI) [38, 48], placing them at risk of being excluded from learning CT. Coding kits often require children to create a set of instructions to help a character (e.g., digital avatar or robotic device) overcome a series of spatial challenges by following a given path, avoiding obstacles, and collecting rewards. We refer to these activities as spatial programming activities as they contribute to the development of spatial cognition [60] which are related to orientation and mobility (O&M) skills, a critical skill for children with VI [15]. Despite the benefits of training spatial programming activities, previous research efforts to make CT accessible to children with VI have mainly explored sequential audio-based actions.

In this paper, we introduce ACCembly, a tangible block-based system accessible to children with VI to perform spatial programming activities. The blocks are physically assembled to program spatial actions, which are made visible through a robotic device with multimodal feedback. We describe the design of ACCembly and how it enables sighted peers (e.g. parents) to participate in an inclusive learning experience alongside a child with VI. At such early ages, parents play crucial roles in mediating learning and play activities at home [20, 53, 74]. Their behaviors and support strategies also influence the quality of children's learning experiences, particularly when using new technologies [33, 55].

We evaluated ACCembly in ecological settings by asking seven mixed visual ability families to use the system autonomously at home. We created an evaluation kit, which included the prototype, recording equipment, and a guide book with activities. We then interviewed parents and children to gather feedback about the use of ACCembly, and analysed video recordings of the families interacting with the system. This study aimed to address questions such as: does ACCembly support computational thinking learning? Does ACCembly allow children with VI to engage in spatial programming tasks? What aspects of ACCembly are effective in engaging children and parents? What roles do parents adopt in mediating usage of ACCembly in a mixed visual ability setting?

This paper contributes with: first, the design and development of ACCembly, a system that allows children with VI to engage in spatial programming activities; second, an analysis of the themes that emerged from video recordings and interviews with children and parents about their experiences with ACCembly; third, reflections on inclusive programming environments that contextualizes its use within a shared family activity. These contributions are relevant to accessibility researchers and designers of technologies for inclusive education, particularly when promoting CT. They provide the basis for designing systems to support inclusive spatial programming activities for children with VI.

2 RELATED WORK

We discuss previous work in four topics of research: first, we analyze related work on promoting computational thinking for children, and the solutions originated from those efforts. Second, we discuss research in making learning CT accessible to children with VI and the relevance of spatial programming for children with VI. Third, we present previous attempts to create inclusive technologies for mixed visual ability settings. Finally, we focus on literature about parents' mediation on children's use of technologies, particularly within accessibility research.

2.1 Computational Thinking for Children

Numerous tools have been developed to teach CT to children, namely through introductory virtual programming environments [16]. Widely known examples include Scratch[50] and Blockly[18]. These offer beginner-friendly versions of traditional textual programming environments, lowering the barriers to learn fundamental CT concepts and practices. Most commencing programming environments use a block-syntax, where children can drag-and-drop graphical representations of blocks to create games, or other visual media. Errors are prevented by design (e.g., mismatched types of blocks do not snap together), enabling children to scaffold syntax learning [67]. Unfortunately, these environments are not accessible to children with VI as they heavily rely on visual ability to create applications and access their output.

Other solutions, commonly known as coding kits, have leveraged the benefits of block-syntax to offer more fun and engaging experiences to children. Yu and Roque classified coding kits into three categories: physical, virtual and hybrid [75]. Physical kits consist solely of tangible components, such as Cubetto[3], a small robot that can be controlled by directional command tiles. Hybrid kits consist of both tangible and virtual components, such as Coding Awbie[44], a tablet game where children use physical tiles to control virtual characters in an open world. Ludi et al. [28], also presented a hybrid environment that allowed LEGO Mindstrom robots to be controlled by an accessible software. Interactive storytelling is widely used to engage children in problem-solving through coding activities. All of these focus on the spatial manipulation of physical/virtual characters as an integral part of the experience. ACCembly builds on the same spatial programming concepts to create inclusive learning experiences.

Tangible components have been increasingly used in commercial coding kits. Tangibles facilitate understanding abstract concepts by combining hands-on approaches with digital feedback [1, 29, 30, 32, 47] and support collaborative programming [22]. Embodied, constructivist, and constructionism theories highlight the importance of manipulating objects, not only to map structural cognitive connections but also to develop refined motor actions, proprioception, and tactile perception [45, 65] - all of these, highly relevant for children with VI [31, 48]. Still, the tangibles in most coding kits are not designed with accessibility in mind, failing to be distinguishable by tact [48]. ACCembly offers a novel approach that leverages block-syntax and provides an accessible tangible coding environment with multimodal output.

2.2 Accessible Programming Environments for children with VI

Prior research has started addressing accessibility issues in block-based programming environments. For instance, Pseudospatial Blocks is a nonvisual language that supports block-syntax coding via keyboard commands and speech output [26]. Blocks4All aimed to leverage screen readers in tablet devices to allow children with VI to explore and manipulate block-syntax applications [38]. The authors also showed that robots could be used as an accessible and engaging tangible output for children with VI.

Others have designed accessible tangible blocks to promote collaboration between children with and without VI [25, 41]. Story-Blocks uses tangible blocks to enable children to create audio stories [25]. The system comprises a camera to read the visual tags on a series of passive blocks and executes the program. Torino uses a set of tangible connectable pods that allow children to read and create music [41]. Others have used similar approaches that combine tangible interaction with audio output to create accessible programming learning environments [52, 61].

Overall, previous research on accessible programming environments is mostly focused on audio-only output [25, 41], leaving aside the engaging nature of tangible outputs, particularly of robotic devices with multimodal capabilities that can move in space [34, 38, 42, 48]. Moreover, current approaches fail to address spatial programming activities that are both needed/valuable to children with VI and are already used by their sighted peers with current coding kits. Spatial programming could also be used to train O&M skills - a milestone in the life of people with visual impairments [23]. To navigate and learn through a spatial map, children gather sensory information about the environment to understand their position in relation to other physical elements, plan the route from the beginning to the final destination, and calculate distance and direction while avoiding obstacles [62]. The use of a map allows to explore and understand spatial concepts and relations between elements [15].

2.3 Mixed-Ability Collaboration

Assistive technologies have been used to promote children's independence, namely accessing visual information via alternative mediums such as Braille, tactile diagrams, and audio. Screen readers and screen magnification tools are still the most commonly used assistive technologies by children with VI. Although designed for autonomy, assistive technologies can have an isolating effect [36], prioritizing accessibility over inclusion; they are intended to be used by children with VI alone and not by sighted users, limiting inclusive experiences.

On the other hand, research on inclusive technologies shows that solutions designed for visually impaired and sighted users can promote collaboration and engagement in joint activities. For instance, Torino was designed and evaluated in large-scale at schools as an inclusive tool for collaborative creation of audio output [40, 41]. Other work developed multimodal applications for learning geometrical concepts [39], storytelling [14], editing diagrams [35], and composing music [43]. More recently, Metatla et al. demonstrated support for engagement between children with mixed visual abilities through multiple technologies, including voice-user interfaces [37] and robotic devices [34]. Neto et al. also leveraged tabletop robots to create inclusive and collaborative drawing experiences in classroom settings [42]. Gadiraju et al. investigated the creation of educational tools to support children with VI in learning Braille alongside their sighted parents [19]. We build on this work of creating inclusive experiences and designed ACCembly to support collaborative learning between children with VI and their parents, teachers, or peers.

2.4 Parents' Roles in Technology Use

There is a large body of work in HCI exploring how parents mediate children's learning [12, 59], and investigating their expectations, concerns, and perceived benefits from technology use [33, 55]. Additionally, family-based learning relationships, particularly parents' roles in mediating play activities, are key when building early expertise with new technologies [5, 20, 53, 74]. More recently, Yu et al. [74] investigated parents' roles regarding their children's learning with coding kits. Based on a literature review [5, 20, 53] and their own findings, the authors identify 10 roles parents could take during the experience and that they frequently interchanged their roles.

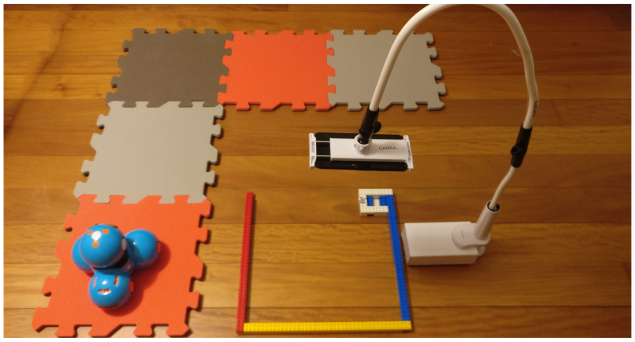
Although there is an extensive body of HCI work about parent-child interactions with technology, research on its intersection with accessible computing is much more scarce. In [19], the authors examined how sighted parents and children with VI learned Braille together using a system comprised of tangible blocks and a GUI interface. Storer et al. investigated how technology can support users with VI (either parents or children) in co-reading [57]. The authors identify numerous co-reading practices affected by social-technical factors such as literacy, social support, and Braille knowledge. They also highlight that parents' roles can go beyond being teachers and include learning as part of an interdependent experience [6] where both stakeholders learn together distinct skills (e.g., print literacy vs. Braille literacy). In this work, we contribute to prior literature on joint media engagement research by investigating learning relationships between sighted parents and children with VI when novel technologies emerge in home settings.

3 DESIGN OF ACCEMBLY

ACCembly is composed of tangible blocks, a Dash robot[70], foam tiles to build a map, and an Android app running on a mobile device. The app uses the device's camera to recognize the sequence of blocks in the workspace, interprets the connected blocks and sends the instructions to the robot.

3.1 Design of Tangible Blocks

We took into consideration the benefits of block-based programming environments, which allow the composition of blocks to create code reducing the cognitive load presented in text-based languages. The tangible block design was based on the exploratory results of[48] with children with VI and their educators. Inspired by [48] results with augmented Osmo Coding Awbie blocks, we designed our blocks to feature magnets and saliences to facilitate coupling,



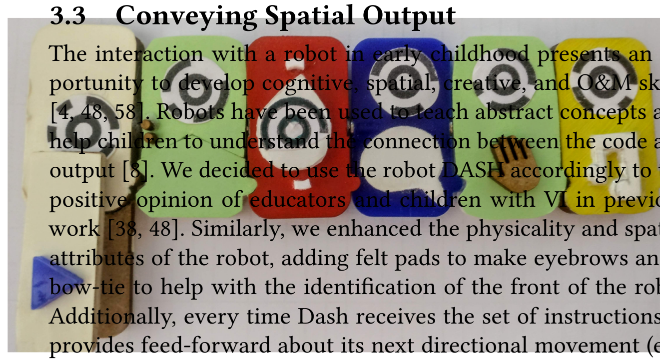


Figure 2: Left) the ACCembly setup: the map, Dash robot, workspace and tripod with mobile device to identify blocks. Right) an example of a sequence of blocks to repeat the instructions moving forward and saying "hi" two times, and then dancing. The white Play block is at the beginning of the sequence, and the green Loop blocks marks the start and end of the instructions to repeat.

and have different colors and embossed pictograms to differentiate the block's actions (Figure 2). Children can recognize individual blocks as well as sequences of blocks via tactile feedback.

There are three types of blocks: action (i.e., Dance and Hi), Direction, and Loop blocks. The yellow *Dance* block has a music note embossed and makes the robot spin while shouting an onomatopoeia via audio feedback. The blue *Hi* block has a speech bubble embossed and makes the robot say *"hi"*. The red Direction block has an embossed droplet-shape arrow to chose the robot's movement direction and makes the robot move one distance unit, which corresponds to one tile of the foam map. The green Loop block can be used to repeat instructions: the start Loop block with two or three dots representing the number of times the sequence will be executed, and the end Loop block with an embossed hand (i.e., stop) to represent the end of the repetition. The Play block has a top part with an embossed play symbol, and a bottom part with the TopCode[21]; the user has to press down the top part to uncover the TopCode below.

3.2 Workspace and Block Interpretation

The blocks are placed in the workspace, corresponding to the mobile device's camera field of view. The workspace is limited by Lego blocks and in the top-right corner, there is an area where users can place any of the blocks (see Figure 2), and the system announces the action that the block represents. A tripod secures the mobile device with the back camera parallel to the workspace. The app in the Android mobile device uses the camera to identify the TopCode located on the top of the blocks. When the Play block is pressed, an auditory cue alerts the user and the mobile app interprets the sequence in the workspace. Then it uses the Wonder Playground API[69] to send the instructions to the robot (Dash). The user can freely manipulate the blocks in the workspace before pressing the Play block. The mobile device and the robot are connected via Bluetooth.

3.3 Conveying Spatial Output

The interaction with a robot in early childhood presents an opportunity to develop cognitive, spatial, creative, and O&M skills [4, 48, 58]. Robots have been used to teach abstract concepts and help children to understand the connection between the code and output [8]. We decided to use the robot DASH accordingly to the positive opinion of educators and children with VI in previous work [38, 48]. Similarly, we enhanced the physicality and spatial attributes of the robot, adding felt pads to make eyebrows and a bow-tie to help with the identification of the front of the robot. Additionally, every time Dash receives the set of instructions, it provides feed-forward about its next directional movement (e.g., "I'm going to walk to the right").

4 USER STUDY

The democratization of commodity coding kits to be used at home enables sighted children to be continuously stimulated and learning, but has widened the gap to children with VI in terms of opportunity. Here, we tried to assess if and how an accessible coding kit could be used at home.

4.1 Participants

We recruited families who had a child with VI between 7 and 14 years-old, through a school with which we have been collaborating. Seven families agreed to participate: (C1) 8 years old girl; (C2) 11 years old boy with a sighted sibling of 8 years old; (C3) 7 years old girl; (C4) 13 years old with a sighted sibling of 17 years old; (C5) 7 years old.; (C6) 11 years old girl; (C7) 7 years old and a 6 years old sighted sibling. Parents age ranged from 34 to 48 with an average of 39.2 years old. Parents education level varied from sixth grade to having a PhD. Parents self-reported technology usage averaged 2.8 (min=1, max=5). One family reported previous interaction with robots or coding kits, and only two parents had any experience with programming.

4.2 Coding Kit and Procedure

We created a remote testing coding kit to be autonomously used by families. It included: (a) the prototype, 12 blocks (2 Dance blocks, 2 Hi blocks, 4 Direction blocks, 1 Play block, and 4 Loop blocks), (b) the Dash robot, the map, recording equipment (one smartphone and one tripod), (c) 4 animal toys (giraffe, elephant, panda, and penguin) to use as targets or obstacles, and (d) a guide book with activities.

We printed a guide book for parents to use ACCembly and guide their children through a set of proposed activities. The guide book starts by explaining how to setup the recording equipment and on how to "setup the coding kit" (A1). The second activity was to "learn the system and the blocks" (A2) with simple tasks of connecting one block to the Play one. The activities started by presenting each block to the recognition zone and then connecting them to the Play block to observe the outcome it produced on the robot. The third activity, "learn sequences" (A3) included the construction of a sequence with different blocks. Through a storytelling task, we ask children to make three simple sequences of 2 and 3 instructions. "Using the system alone" (A4) presented an obstacle that the robot should avoid with the aim to force children to use more varied paths to arrive to the target. In A5 "learn looping blocks" children need to recognize patterns in the path and to successfully use the Loop blocks. Finally, in A6 "create your own story" children were motivated to create their own story and make the sequence of movements and actions to accomplish their goal. For each task, the child should manipulate the tangible blocks to move the robot and achieve the proposed goal. There was no time restriction or limited number of trials. Participants were also encouraged to explore the system and the blocks besides the proposed activities.

We contacted parents and one researcher personally delivered the coding kit to families. Children received the researcher with enthusiasm, excited with the possibility of playing with a robot at their home. We asked parents to start by following the guidebook and its activities, but also to allow children to freely explore the setup. After children and parents interacted with ACCembly, we conducted a semi-structured interview with them to gather their opinions and suggestions about ACCembly, its values and limitations, programming knowledge acquisition, and collaboration.

4.3 Data Analysis

We analysed videos of the families interacting with ACCembly, and the transcriptions resulting from the interviews with parents and children after interacting with ACCembly, following a mixed thematic analyses [9, 10]. We sought to observe specific codes related to children's CT learning and engagement in a family-based interaction driven by theoretical frameworks from psychology, learning and HCI. After generating theory-driven codes, we created data-driven codes that were relevant and strongly linked to the data. Two researchers iteratively codified data until a full agreement of the codebook was achieved. Then, the two researchers organized codes in themes; reviewed and redefined themes, and organized them into a coherent and consistent story about the data [51] [71].

5 FINDINGS

This section describes the main findings emerging from parent-child interactions when using ACCembly in a mixed-visual-ability home environment.

5.1 Initial Exploration of ACCembly

Before starting the CT activities provided in the guide book, families engaged in physical, unstructured and exploratory experiences with ACCembly. When children first interacted with ACCembly, they mainly expressed amusement as they saw the robot moving as instructed by the blocks: *"when she started to see it [the robot] moving, responding to the things she wanted, she found it very funny and amusing. She played for about one hour in such amusing play."* - Mother of C1 (M1). This initial exploration served to understand the setup, the blocks, and the available actions to command the robot: *"They did explorations [...] assembled together the different blocks to see what the robot could do. And it was fun to see, now it dances, now turns to the right, then to the left. We could see what its abilities were.*- M1.

C3 and C4 were the only participants that did not follow any of the structured activities in the guidebook. C3 spent 7 hours physically playing with the robot. She enjoyed its shape, bright light, and multiple sounds: *"she really liked [the robot], because it speaks a little bit, has lots of lights, she loved that part [...] But she couldn't use any of the blocks. Often what happened was - I put the block, the robot did what it was supposed to do, but then she would grab the robot and pull it back. She really wanted the robot, to touch it, to be with it [...] she did not have the curiosity to use blocks"* - F3. C4 also interacted with ACCembly in an exploratory manner, much due to the parent's mediation behavior; the mother randomly placed the targets and the robot on the map without giving C4 any cue about their locations. The experienced turned to a non-goal-directed activity which limited the child's experience as she placed the blocks in the workspace without a clear goal such as to go from A to B.

After the initial exploration of the coding kit, we observed C1, C2, C5, C6 and C7 engaging with ACCembly in a structured and goal-driven way by following the activities in the guidebook.

5.2 Interacting with the Robot and Tangible Blocks

In this section, we analyze the emerging behaviors of children when interacting with ACCembly, namely the robot and tangible blocks.

5.2.1 Robot's multimodality. Parents highlighted the importance of the robot's multimodal attributes to engage their children and invoke curiosity. Light and sound seemed to play a vital role: *"She could see the big light in the [robot's] eye [...] understand if it's spinning, by observing where the light is"*- M4. Children could also rely on the tactile cues of both the eyebrows and tie, critical to understanding the robot's position and front side. The robot also verbally indicated each instruction before executing it. Such features engaged and afforded children to have more control and autonomy in the interaction: *"The robot makes noise when moving, which is good, [...] gives them a reference of where it is."*-F7.

Overall, children were very enthusiastic about the robot. They especially enjoyed (they laughed and applauded) when the robot accomplished the goal, or crashed with the targets. Such a positive experience was further highlighted when a child asked us: *"could you bring me more robots to play with?"* -C3; or by the words of M1: *"the robot has conquered a place at our home"*. It was also frequent to observe children scream to the robot, call it, or talk to it, which could be related to children's tendency to anthropomorphize the robot. Examples include C1 asking *"Can you excuse me?"* when picking up Dash and moving it from one place to another. Similarly, C5 often sang to the robot, and C3 named the robot and created a story for it.

5.2.2 Accessibility of Tangible Blocks. ACCembly is composed of different tangible blocks to represent various actions: Direction, Hi, Dance and the Loop block. We observed that children understood how to use the blocks to command the robot, and were able to describe each block's functions and the specific outcome produced in the robot. Children enjoyed the use of the blocks and each one identified the block's colors, material, and tactile forms. This was also corroborated by parents: *"[C1] understood which blocks she needed and in which order and orientation should the blocks be, to [command] the robot"* - M1. The availability of multimodal cues such as textures, colors, and embossed pictogram, allowed children to use the most useful feature for them:C5 relied on block's pictograms, C4 on block's textures, C1 and C6 on it's colors, and C2 relied on a combination of features such as texture, pictograms and colors.

Parents also positively commented on the blocks: *"I think they're cute, blocks have a good size, they are well made, they fit very well, they communicate well"*- M1; *"it turns out to be very intuitive and not difficult to fit ... [and to learn the] mechanics, always from left to right."* - M2 and "the magnet helped to fit the blocks " - F6.

Parents and children mentioned that it would be relevant to add braille labels. C4 noted that the use of bigger blocks would ease their manipulation and identification. Regarding the Direction blocks, C4 mentioned: *"that one was easy to understand, I could see that it was for moving."* and F2 commented: *"I think it [joining blocks] works very well ... that steering wheel works with the pointer, it works very well"*.

5.2.3 Sequences and the Loop Block. While using ACCembly, children often applied CT concepts, like sequences and loops, and all children - except C3 - were able to demonstrate their ability to match a programming command with its outcome or action. We also observed that children quickly understood that the code was built from left-to-right. C1, C2, C5 and C6 started building sequences with the help of their parents, working in collaboration.

Regarding the use of loops, C2, C5 and C6 achieved that level of proficiency. C2 and his sibling understood the loops easily and took turns to apply it: *"Rigt, forward, right, forward, isn't it? ...So I put a straight block here, isn't it?"* - and he puts the right turn and the straight blocks inside the loop blocks. C5's family had some difficulty understanding the loops at first. They examined the block and re-read the guidelines. During the final interview, C5 asked us *"if I put the Dance block and then the Loop block to repeat 2 times and add another Loop block to repeat 3 times, would the robot dance 6 times?"*. The question demonstrates that C5 was able to grasp and apply the loop concept to a different situation, exhibiting a significant level of understanding, abstraction and reflection. F6 challenged C6 and she identified that the robot had to go forward twice and once to the left. She used the loop blocks to repeat forward, and put the left block after the end of the loop.

5.3 Applying Computational Thinking

Our analyses revealed that the use of ACCembly elicited the use of different CT concepts and competences. *Problem decomposition* was observed when the child broke down problems into smaller and more manageable components. Examples include moving through space to touch possible paths for the robot and thinking aloud the steps needed to achieve the goal. Children manipulate blocks, rotate arrows, and re-arrange sequences while considering their siblings' and parents' suggestions. Problem decomposition often occurred before families started building their algorithms and procedures. For example, M5 stated the goal, C5 thought about the solution while the mother confirmed he was right.

We observed *Data Collection* when the child gathered relevant information to solve a problem; for example, assessing the robot's location on the map, counting how many cells from the robot's location to the goal, or asking their partners for help to finish their reasoning. Parents often explained and confirmed what was happening. For example, C7 would crawl on the map searching for the robot and the toys to gather relevant data.

We codified *Algorithms and Procedures* when the child followed, identified, used, or assembled an ordered set of blocks. These were usually preceded by children thinking aloud and/or listening to parents' contributions (explanations, suggestions, and corrections), and then by manipulating and joining blocks to build the solution. Children would often count how may cells should the robot move, and in what direction, and then place the corresponding blocks. Finally, they would iteratively check which blocks were still missing, by counting the map's units, until they had created the whole sequence of instructions.

Pattern recognition was observed when children had to use the Loop block. To use the Loop block, they needed to identify patterns in the possible paths as illustrated by M5:*"the robot had to go to his friends; it had to go forward, right, forward, right. We had to think how to use the Loop blocks."*

Debugging was coded when the child identified that the output was not the desired or the system was not responding correctly. It usually occurred after *algorithms and procedures*. Typically, parents became logistics supporters and started testing the system. They manipulate the blocks, press the Play button, check the robot and the mobile phone's connection. This is normally followed by a second try to achieve the goal. For example, on one occasion, C1 did not rotate the arrow enough for the robot to turn right, so the robot went straight. Her father explained what happened and that she had to rotate the arrow further to the right. She followed the correction and the robot met the goal.

5.4 Practicing Spatial Skills

Our setup with a tactile map and spatial goals embedded within a storytelling afforded the direct use of spatial cognition, namely O&M skills, spatial awareness, body-scheme, mental rotation, perspective-taking, among others. Children gathered the sensory information needed to understand the environment and effectively command the robot to perform the spatial activities. The multimodal environment, ACCembly, afforded children to detect the map, robot and targets haptically, and to listen to the auditory feedback of the robot. The robot multimodal feedback allowed children to gather sensory information about the robot's location and it's actions at each step. For F7 *"the system was useful to develop the need to feel, to use touch; she had to realize that she had to give instructions and the reason why."*-F7.

To gather information about the map, children touched, walked or crawled on the map and counted the number of units and the direction to arrive to the destination. These actions helped children to understand laterality concepts and instruct the robot to navigate in the map. These activities could be important to train O&M skills as mentioned by M7: *"[laterality] concepts are still difficult for her [...] left, right, front ... so I found it extremely interesting, because these are the concepts that we are working on at the moment, because of mobility and because we are now introducing the cane"*.

In the interviews, we found that for some parents the dimensions of the map were appropriate as it permitted children to walk on it, but parents also mentioned that it would be interesting to have a minimap to allow the whole perception of the environment "at hand" and that "the minimap could be in the guidebook" -F7. But M7 reflected and concluded that "then, children would end up not exploring the space. It would not be positive". Another suggestion concerned the use of "different textures and references in each unit" -M7. The targets located in the map could have a fixed position in the map to avoid searching them or the robot as suggested by F7, which added "If there was a fixed pole, like Velcro or a fit [it would be more easier, like LEGO, more precise [...]".

Children needed first to understand where the robot was located and to which direction it was facing before starting to set the instructions. C1, C2, C5 and C6 were able to correctly apply perspective-taking to command the robot with the parents' help. Parents were critical facilitators, alerting children that the robot is turned to another direction, correcting children, and motivating them to consider the robot's reference frame and not the children's reference frame. Only C2 amazingly understood perspective-taking from the start and also corrected his sister (2 years older). The father said many times: *"remember you're the robot"*, to remind the sibling that she should take the perspective of the robot.

Parents were crucial in the process of spatial conceptualization. They would often direct children's attention to spatially relevant aspects of the environment - spatial talk [54]. Parents' *spatial talk* is a predictor of children's learning of spatial concepts [54]. On the other hand, when children use spatial talk, is because they understood such spatial concepts [63]. For instance, C1 talked aloud: *"First, the robot must go to the right [while touching the cell she is referring to] then keeps going straight to the giraffe and then can go here [touching the end cell]"*.

5.5 Mediating Interaction and Parents' Roles

We analyzed parents' roles based on the parental mediation framework proposed by Yu et al. [74], which features 10 roles. In the case of C1, C2, C5, C6, and C7 parents interchanged roles throughout the activities; they were *teachers*- parents teach children how to do something -, *collaborators* - parents and children share a learning experience -, *logistics supporters*- parents help with the logistics of children's play -, *scaffolders*- parents suggest different ways of playing -, *spectators*- parents act as an audience -, and *enforcers* (when siblings played together)- parents enforce rules -, while M4 had mainly the role of *dominator*- - parent take over the experience from their children[74]. F3 had the role of *spectator* and *gatekeeper* - parents test the coding kit before and manage access to it - by preparing and testing the setup; however, C3 did not engage in the proposed structured activities.

Parents usually began with a teacher's role, explaining how to use the blocks, reading the step-by-step instructions, and describing the general rules of the system (while the other parent, if present, would have a role of *scaffolder* or *logistics supporter*). The parent with the *teacher* role would stand next to the recording camera and read the instructions of the guide book, eg.: *"the father read the instructions and then explained them. He adapted the instructions to her: it works like this, if you join [the blocks] like this [showing how to join the blocks], now press play there [pointing] and see what happens."*- M1. If there was a second parent (M2, M5, F7), they would be located closer to the children, helping them identify and demonstrate what the teacher-parent was reading, such as giving and announcing the block and explaining how to assemble and press play. They could interchange between *logistic supporter* - help with logistics, such as re-positioning the robot or setting up the kit- and *scaffolder*. These roles were also observed in C2's sister.

M4 adopted the role of *dominator* throughout the interaction. She would often say *"change the block"* without explaining why or giving C4 the opportunity to engage. M4 would randomly put the toys and the robot on the map, and frequently pressed play while covering the block's Topcodes, which impaired the child's experience with ACCembly. Although it was challenging for C4, she accurately named all the blocks and the associated robot's actions in the interview. On the other hand, the role of *enforcer* was only observed when siblings played together (i.e. C2). The siblings became competitive at times, and parents required them to turn-taking. These were the only parents to have the role of *spectator*: *"you are the ones who have to do these [activities]. Mom and I will keep silent"* - F2.

We observed a strong collaboration between children and parents, especially in C1, C2, C5 and C6 families. During the first activities, children were usually following the parents' instructions to get familiar with ACCembly. Parents helped children build their understanding by giving suggestions and questioning, throughout the session, having mainly the role of *scaffolders*, which afforded children opportunities to show initiative and enthusiasm to solve the activities. When parents had the role of *collaborator*, children were more prone to express their thoughts and collaborate with the parent towards a solution: they would talk and ask questions to each other, and come up with ideas together. Parents offered help frequently, particularly by giving out blocks, helping them building sequences step-by-step, exemplifying, making suggestions, correcting, stating goals, or confirming whether their code was correct. In the last activities, we noticed parents letting children to be more autonomous by challenging them to develop solutions by themselves.

C2 had the most collaborative experience along with his sighted sibling. The sibling frequently collaborated in reasoning and decomposing problems. While she manipulated blocks, read instructions, made suggestions toward the solution, or gave logistical support, C2 would be thinking aloud and working cooperatively towards the goal, indicating the robot's location, intended direction, and assessing distances on the map. Then, they would often revert roles. They spent most of the time collaborating; e.g., while one chose the blocks, the other placed them in the area (Figure 1).

5.5.1 *Facilitating Learning and Engagement.*

We observed children to be highly engaged with ACCembly which is central to effective learning [66]: *"she spent two hours with her father, entertained, just doing that"*- M1. Parents had a crucial role by reinforcing engagement, mainly through scaffolding, giving positive reinforcement and asking questions that made children willing to engage in further explorations. Parents would frequently explain in different ways or exemplified when children got stuck or asked for help. To maintain children's engagement, parents would empower them by giving verbal support or redirecting children's attention to the activity (e.g., *"Come on, concentrate"*- F5). Examples of verbal support were vast (e.g., *"Congratulations! You gave instructions to your robot!"*- M5, *"Did you see? He said HI because you placed those two blocks - F1"*. Emotional verbal support was also vastly observed (e.g.,*"You've* *done it! You're spectacular"*- F1), and emotional physical support such as an high-five between C5 and his mother.

We analysed how children were engaged with ACCembly in three dimensions essential for effective learning [66]. We observed that all except C4 showed *affective engagement* - emotional responses to the activities in children's learning experiences - with the setup (or with the robot as in the case of C3). C3 had such a strong *affective engagement* with the robot that it may have prevented her to engage cognitively and operatively with the kit. We also observed that all children except C3 showed some level of *cognitive engagement*- a psychological state where children put their efforts and cognitive resources in the learning process. They sought to understand what were the block's actions, how to give instructions sequentially, and reasoning about what they were doing, such as *"if I do this, then the robot goes there"* -C1. Lastly, we also observed *operative engagement* - the involvement to work towards a solution. The fact that children had goal-directed activities, engaged them in working towards possible solutions. Children debugged, corrected directions or blocks, decomposed the problem, created the algorithm, and planned paths. They were able to engage in the operations needed to accomplish the proposed activities' goals, and even created their own stories, challenges, and novel solutions. For example, C2's sibling said: *"I already have my story planned [...]"* and C2 replied, *"I already have my program all done, all decided"*. They were in a positive competition and each one created their own story. C2's story was: *"Dash and friends were at Dash's house one day until the penguin had an excellent idea of going to an ice rink. But the ice rink was on the other side of the city and closed at 9pm. We have to find the shortest way to get there in time and slide together"*. M2 quickly added a toy snow sled to mark the ice rink collaborating and turning the activity more engaging.

The interaction with ACCembly prompted children to use epistemic actions which are relevant for learning [2]. These are performed to achieve a solution without directly being the solution, such as preparing the arrow direction or the sequence of actions before attaching them to the Play block, or walking through the map following a certain path. These actions reduce the apparent choices, offload cognitive resources and spatial reasoning to the physical objects, which in turn may facilitate understanding of complex concepts [1, 2].

5.5.2 Parents' Expectations. Parents enjoyed the experience of interacting with ACCembly at their homes, as a family activity: *"it ends up bringing the family together. And it's something that sometimes, due to work, day to day, with obligations, we have difficulty getting together, and it's even funny, because it was just a moment of union at the end of the day and it's cute, we as parents we like that"* - M1. Parents mentioned their expectations about what the system could bring to their children: *"I hope this will evolve because we really need it, I think that in this field [computing] things are really evolving. Our children are missing this!"*- M4. Parents mentioned that this type of tangible coding kits would help: *"Understand the dynamics or mechanism that involves programming; I think it is a very easy way to learn."* - F5, and M5 continued: *"And it requires planning, it requires construction [...] there is a great satisfaction at the end, which is the goal [...], and there are moments of reflection. The person assembles, sees that made a mistake, tries again. You can build, fix"*.

When asked specifically if parents think the experience could have led to use some CT processes parents were positive: *"I think she is aware that when she put the blocks together and pressed Play, that [... by] joining those blocks [she] instructed the robot to move the way she wanted"* - M1 . The mother continued *"She may not have realized that she was creating a sequence. But she was aware of which blocks she needed so that the robot could do what she intended to"*; when listening to the mother, the child asked *"what are sequences?"* and the mother replied that *"the sequence was the order in which you put the blocks so the robot did what you have decided"*; and the child replied *"ah! yes, I understood that!"*.

Parents also expected that children would use the system independently and autonomously without their involvement: *"as [C1] already did and has a notion, I think she could very easily do it alone, and even explain to her colleagues [how it works] [...] I think they need to start practicing in a protected environment, with support, and then they would have more autonomy"*- M5. Another consideration to afford children's autonomy would be to have *"the stories written in Braille.[...] Or audio, an audiobook, for example [...] and for children with low vision, the size would have to be increased."* - M7.

M2 envisioned the use of the kit at school: *"In groups of 3 or 4 I think it would work well. Each one ends up having a role; one to read, the other to help, and one to do. Sometimes [C2] and his sister would compete [to use ACCembly]. But they quickly realized, now do one, now do the other, now you press the button, etc..."* referring to the need of children's turn-taking and to divide materials, specially in the school context. F7 mentioned that *"at preschool age, kids are stimulated to develop laterality, mobility [...] there are schools and teachers with the notion of programming benefits"*. M7 suggested to embed spatial programming in teaching *"math, to play with numbers. At school, would be an excellent option"* - M7.

F6 suggested to use ACCembly as a *"board game to play with more people... in teams, [for eg.] there are two robots; one robot passes in front of the other- a race between robots. if [ACCembly]] were more like a game- as we have many here at home- it would have some potential for play, more as a competition game, of teams"*.

5.5.3 Parents Technological Experience. The parents and children that participated in our study did not have previous experience with coding kits, except F6. The lack of experience could have represented a challenge when they used ACCembly for the first time: *"I confess that I read the guide book and did not understand anything, I thought: 'what did I got into?'"*- M2. Still, parents were able to overcome such challenges by following the step-by-step guide book: *"But ... when my husband started taking things out of the box [...], when he started assembling and realizing what he was supposed to do, it [the guide book and the kit] was quite accessible and it was simple"*- M2.

We observed that problems with the system made parents change their roles from *scaffolder* to *collaborator* or *logistic supporter*. Some parents were more proactive in solving technical problems, while others were not. When the camera did not detect the blocks, parents started troubleshooting it by moving the camera, changing blocks, checking if the app was ON, or if the smartphone was well-positioned. ACCembly could stop working if: app was OFF, smartphone ran out of power, light detection problems, codes covered by a hand, or the Play block was not connected to the other blocks.

M4 said that she was very engaged and appreciated the experience; however, because she perceives herself as not being savvy with technology, she felt she could not support C4 any better. She tried her best. During the interview she reflected: *"[C4] for sure would be able to use the setup by herself and she was able to understand it"*. However, we noticed that in this case, C4 did not have much opportunity to engage with ACCembly. Although the fact that the mother took over the experience, probably to explain it to C4, she did not know how to provide such support.

6 DISCUSSION

We describe the design of a fully-tangible (input and output) spatial programming environment for children with VI and the results from its deployment at mixed visual ability families' homes. We found that ACCembly was an engaging and fruitful environment to promote the use of CT competencies and spatial cognition. In addition, investigating the use of learning tools in home environments, particularly coding kits, is relevant because its availability and usage outside school settings became more frequent. In the following sections, we discuss what aspects of ACCembly were effective in engaging children and parents, and how it supported shared learning experiences of spatial programming.

6.1 Multimodal Robots, Tangible Interaction and Engagement

Among the wide variety of coding kits, using robots has been a popular topic in education because they are attractive and relevant to learn complex concepts [8] and increase engagement in social and collaborative actions [8]. There have been efforts to provide children with VI with the means to interact with robots [34, 42], but few studies explored spatial activities. Blocks4all [38] used an onscreen block-programming language to move a robot. The study revealed that it was challenging to program using the virtual interface to the point that jeopardized performing the activities. [48] studied the qualities of off-the-shelf robotic environments and found that robots were a motivating artifact to reinforce causal relations and mappings, and that tactile blocks could strengthen children's perceptual abilities.

We used a multimodal robot to motivate children to program spatial activities. Findings demonstrate that combining tactile feedback (robot and embossed marks) and audio feed-forward (the robot announces its actions) enabled children to assess, plan, and debug spatial programming activities. Using a tactile map and targets also helped children to be aware of the robot and target locations and possible paths. Children could gather relevant sensorial data to approach the goal, recognize patterns in the map, and plan the algorithm and procedure to achieve the goal. By accessing the robot output, map, and selected blocks, children could also understand errors and start a debugging process.

The multimodal nature of blocks (shape, color, embossed pictogram, and audio) successfully cope with children's individual differences. They used a single or a combination of features to identify blocks. In addition to providing an accessible and effective way to program a robot, tangible materials allow children to distribute parts of mental operations into actions on physical objects, which decreases the cognitive load [2] in the learning process (e.g., programming). Embodied actions with objects, such as the ones afforded by ACCembly, helps in the abstraction and integration of complex concepts and increase refined motor actions, proprioception, and tactile perception [45, 46, 64]. Children would frequently do embodied actions to help them incorporate spatial concepts, such as perspective-taking, laterality to instruct the robot's next moves. This is particularly important in the context of children with VI. Spatial skills play a crucial role in fostering multiple STEM achievements [56] and in orientation and mobility skills [15, 27]. Perspective-taking is the foundation of *Theory Of Mind*, also crucial in the development of any child [72].

Our study highlighted that using an inclusive robotic environment that provides multimodal sensory information promotes engagement and learning. The physical integration of multiple sources of information to represent one concept is also favorable to learners- the cognitive association between the elements becomes available to the perceptual system, which releases attentional and working memory resources. Such multimodal features afforded and engaged mixed visual ability families in playful programming experiences. Tangibles prompted more interaction between family members, as they afforded numerous actions, ensuring a more playful and inclusive experience than virtual elements [20]. Our findings support that tangible programming environments with multimodal robot output are engaging for both children with VI, their sighted parents and siblings.

6.2 Family-based Computational Thinking Learning

Technology has the potential to enhance parent-child interactions and mutual engagement to support qualitative play [20]. The use of ACCembly at participants' homes provided an enjoyable play experience as participants seemed to genuinely enjoy to command the robot and completing activities. Families valued the experience as an important time spent in family, where all members could participate and collaborate. Parents envision the use of ACCembly as a playful tool to train children's programming and spatial skills.

Parents would interchange roles depending on children's needs and understanding of the activities. They would often start by having the role of *teachers* to explain ACCembly and the steps needed towards a solution. They quickly transitioned to *scaffolders*, *logistical supporters* or *collaborators* to increase children's autonomy and leadership in the activities. Although most of the parents did not have previous experience with coding kits, they understood it and guided children throughout the activities (except M4). Parents used diverse mediating roles to explain and instruct children, such as asking questions to test their understanding and decide when to move to the next concept or activity. Parents valued the time they spend together collaborating and solving the activities but they also commented that they would like their child to be autonomous in the use of ACCembly. Coding kits at home should afford both opportunities, giving children more agency and control (e.g., guiding them throughout the activities [24]) and suggesting activities for parents' collaboration or competition. This goes in line with previous research on the need to include design features to support parent's roles in learning technologies [74]. It is especially relevant when parents are not able to properly scaffold or support children's play (e.g. M4). We contribute to this area by contextualizing the use of programming environments by children with VI and their parents. We observed that parents often assumed a *collaborative* role in providing visual information to children, such as assessing the direction the robot was facing, counting cells, and understanding sequences of Direction blocks. Future work should consider the trade-offs between easing this process by adding new features to the system and limiting collaboration opportunities.

We studied the use of ACCembly in an ecological setting - children's homes - which has a great potential as children may feel safer and nurtured and behave more naturally. In such a nurtured context, children could be more interested and engaged in STEM activities. However, ecological settings may decrease internal validity. The study of ACCembly deployment at home depended mostly on parents mediation and their technological abilities and support, and on video recording the interaction. In order to facilitate ecological deployments, the future version of ACCembly could leverage the acquisition of a more accurate mental model of blocks' detection with an explicit auditory explanation and the possible solutions to technical problems.

6.3 Limitations and Future Work

This study was limited to three days at each child's home, making results subject to a novelty effect. A longitudinal deployment with more participating families is necessary to assess the impact of long-term usage in engagement and children's learning.

Although parents claim they recorded most of the interactions with ACCembly, they also assumed not recording all, leaving aside situations they found were not useful or unsuccessful and this could be related to what parents thought was desirable for the researchers - the desirability effect. In the interview, parents commented that sometimes they did not record the cases when they were by themselves testing solutions to the activities: *"we tried to record only the part that we were doing the exercises. Otherwise, [the researcher] would be hours and hours seeing the videos."*- M1.

7 CONCLUSION

Prior work on accessible block-based programming environments has been focused on audio-based challenges. Children with VI have been limited from engaging in spatial programming activities as their sighted peers do. We bridged this gap with ACCembly, an accessible block-based environment that enables children to control a robot. We evaluated ACCembly with seven mixed-visual-ability families at their homes. Findings show that ACCembly was effective in supporting shared learning experiences and enabling the use of CT concepts. Children employed multiple spatial skills while programming navigational tasks. Parents took on various roles throughout the activities, mostly shifting between teaching and scaffolding. Based on these findings, we further reflect on the implications for the design of inclusive programming environments and evaluation methodologies to support learning experiences in home settings.

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8 SELECTION AND PARTICIPATION OF CHILDREN

The research protocol was approved by the Ethics Committee of *Faculdade de Ciências* - CERPDC. We contacted and recruited families with a child with VI through collaborations with inclusive schools in the Lisbon area. Parents/legal tutors signed consent forms to allow their participation, which included a full description of all activities, analysis and future usage of the collected data. All children assented to participate and understood that they could quit anytime. Activities were designed for a positive/playful experience. Parents video-recorded the activity.

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