Exploring Accessible Programming with Educators and Visually Impaired Children

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ABSTRACT
Previous attempts to make block-based programming accessible to visually impaired children have mostly focused on audio-based challenges, leaving aside spatial constructs, commonly used in learning settings. We sought to understand the qualities and flaws of current programming environments in terms of accessibility in educational settings. We report on a focus group with IT and special needs educators, where they discussed a variety of programming environments for children, identifying their merits, barriers and opportunities. We then conducted a workshop with 7 visually impaired children where they experimented with a bespoke tangible robot-programming environment. Video recordings of such activity were analyzed with educators to discuss children's experiences and emergent behaviours. We contribute with a set of qualities that programming environments should have to be inclusive to children with different visual abilities, insights for the design of situated classroom activities, and evidence that inclusive tangible robot-based programming is worth pursuing.

Author Keywords
Programming, Visual Impairments; Children; Educators; Accessible; Tangible; Robots.

CCS Concepts
•**Human-centered computing** → **Human computer interaction (HCI);** *Haptic devices;* User studies;

INTRODUCTION
Computational thinking (CT) emerged as a discipline in schools, including kindergartens. The pillar concepts of CT are pervasive in our lives and go beyond usage in computing contexts. Training CT promises to develop children's abilities and prepare them for their lives, fostering personal and career development [52]. Promoting CT has been increasingly performed with programming activities. The advent of visual programming environments, like Scratch [40] or Blockly [16], democratized programming in schools. These allow children to create highly visual applications by composing virtual blocks. The use of tangible blocks has also been used as a way to facilitate understanding of abstract concepts, reduce cognitive load, and promote CT, while simultaneously developing motor, perceptual and cognitive abilities [19]. Programming a robot, with these environments (virtual or tangible), is another trend that increases the physicality of the programming output, and provides a greater sense of control [44].

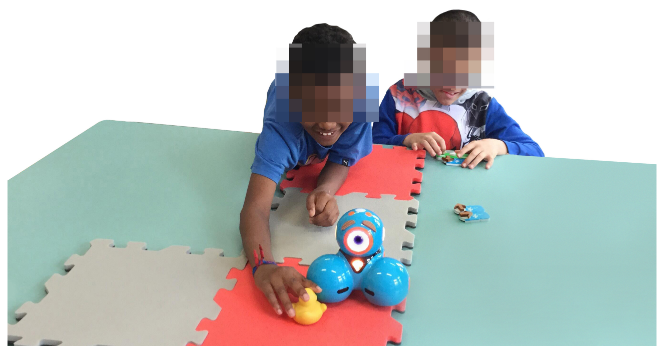

Figure 1. Two visually impaired children performing a goal-directed spatial programming activity in Study 2.

Such approaches and artifacts are now mainstream, widely available, and affordable. However, they are not accessible to visually impaired children. There have been efforts to make programming environments accessible or to devise novel tangible programming setups that bridge this gap [31, 45]. Despite such efforts, we have still not reached a state where visually impaired children can perform the common spatial programming activities sighted children do, and take full benefit of training spatial cognition along with CT training.

In this paper, we extend prior work on accessible programming environments by taking a principled approach that builds on established knowledge and explores opportunities for spatial activities. We conducted a focus group with 6 educators and

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discussed the values, limitations, and opportunities of multiple programming environments for visually impaired children. Building on such findings, we adapted a mixture of solutions and used it as a design probe with visually impaired children (Figure 1) to expand on the potential impacts of such a solution on a classroom.

RELATED WORK

Promoting CT in young children has been increasingly explored through block-based virtual environments [7]. These allow composing blocks to create applications that are highly visual and aesthetically pleasant. The color of the blocks supports children by helping them in recognizing functions and which blocks can be composed together [50]. This process reduces the cognitive load of text-based languages. Scratch [25] is a popular example of an environment that allows children to tinker with blocks to produce applications.

Screen-based programming environments, like Scratch, are not accessible to visually impaired children [24, 6]. Previous work has tried to bridge this gap with solutions that leverage accessibility services, as screen readers (e.g., Blocks4All [31]). Albeit promoting physical access to the setup, it is still a question if these environments can be made accessible to a level that is attainable to younger children and support learning.

Tangibles facilitate the understanding of abstract concepts combining hands-on approaches with digital feedback [1, 26, 27, 29, 36]; highly relevant for visually impaired children ([28, 37]. 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 [33, 35, 48].

Some solutions explore the manipulation of tangible blocks as a way to increase the physicality of the activity and reduce cognitive load. Paradigmatically, these approaches have not been designed with accessibility in mind, and fail to include visually impaired children. Strawbies [19] and T-Maze [49] are examples of solutions that feature visually but not tactually distinguishable tangible blocks and graphical output.

To bridge this gap, researchers developed accessible tangible solutions with audio output. StoryBlocks [21] adopted the block-based approach to enable the programming of audio stories. Project Torino [45, 32] steps away from a block-based approach to present an automata-based one with the goal of constructing musical output. Such projects gave the first steps towards solutions that are inclusive for visually impaired children but have done so in a limited context (sequential audio-based actions), that are not representative of the full gamut of activities used to promote CT in schools, such as spatial activities that also promote spatial cognition, a skill of extreme importance for visually impaired children [47].

The output is a crucial component of computer programming and pivotal to the acquisition of CT concepts. Several solutions consider robots as the means for output. The interaction with a robot in early childhood presents an opportunity for the development of cognitive, creative, and communication skills [4, 44]. While not explicitly designed to be accessible, robots lower the barrier for usage given their physical affordances. A robot can be touched, followed, and heard. As an example, in Blocks4All [31], the programming environment was screen-based, but the program controlled the DASH robot. In their study, they confirmed that visually impaired children could follow and understand the robot's actions.

There have been attempts to create accessible tangible solutions, like CardBot [38] and P-Cube [5], that used low-cost material blocks and use a robot as the programming target. However, these solutions have been limitedly explored with the target population, and there is no clear understanding whether and how these environments are enabling programming and CT training in classrooms.

Our approach is inspired by established solutions and practices grounded in theory, and seeks a comprehensive understanding of how, and whether, these could be made accessible. To do so, we involved educators and visually impaired children in our design activities, following the best practices in the literature [12, 30]. In a first study, we take a retrospective look at established solutions and extract the qualities and gaps of such approaches; in the second, we prospectively inspect the performance of a bespoke accessible environment and derive opportunities for future environments.

STUDY 1: EXPLORING CURRENT APPROACHES

Approaches to promote CT with spatial activities include fully virtual environments (e.g., Scratch with virtual output), virtual programming environments with tangible output (e.g., Blockly and Wonder for DASH or a drone), tangible programming environments with virtual output (e.g., Osmo Coding AWBIE), and fully tangible programming environments (e.g., Wonder Puzzlets for DASH, Clementoni´s DOC robot). Several of these have been adopted in schools' curricula, aimed at different ages, with situated tasks and accessories (e.g., maps). None of them is fully accessible to visually impaired children. In this study, we selected examples of the aforementioned CT environments that had at least one tangible component (robot and/or blocks), leaving aside the fully-virtual setups, that have shown to be too complex and restrictive for spatial tasks [31]. Together with special needs educators (SNE) and information technology (IT) instructors, we sought to understand the values and shortcomings of such environments, with this overarching question in mind: could these environments be accessible to visually impaired children, and which qualities should be prioritized?

Participants

We recruited 4 SNEs and 2 IT instructors from the primary and secondary inclusive schools A (Table 1); such schools accommodate children with different abilities, and are the reference schools for visually impaired children in Lisbon.

Procedure

We selected different types of CT environments focused on spatial activities (Figure 2) for the focus group. For each environment, we presented its features and demonstrated the most relevant, we commanded the virtual character or robot to perform an action, a sequence, and walk a square (when

Table 1. Educators that participated in Study 1 and 2. Table indicates their age, sex, school and years of experience as SNE or IT instructor.

	Age	Sex	School (A, B or C)	Years of experience
SNE1	57	F	SNE coordinator (A)	32
SNE2	44	F	Primary (A)	13
SNE3	NA	M	Primary (A)	NA
SNE4	37	F	Secondary (A)	13
SNE5	37	M	SNE coordinator (B)	12
IT1	57	F	Secondary (A)	38
IT2	NA	M	Secondary (A)	NA
IT3	47	F	Pre-primary (C)	4

NA: No Answer

possible transforming such sequence into a loop - not possible with DOC and PUZZLETS). While educators interacted with each environment, we motivated brainstorming to identify qualities in each setup, ideas, and opportunities for in-class activities with visually impaired children, and wrote-up such ideas on post-its. At the end of the session, we asked for general opinions and debriefed the participants. The workshop session was audio recorded.

We started the focus group by presenting one fully tangible environment: Clementoni´s DOC robot with buttons on its head (turn right, turn left, walk, OK) that comes with two colorful themed maps. Secondly, we presented a mixed environment where the input is virtual and the output is tangible, the robot DASH (Wonder Workshop). We showed Dash's capabilities (moving, turning, head rotation, light switching, obstacle and sound sensing) by using the BLOCKLY environment to command it. Third, we presented another mixed environment, Osmo Coding AWBIE. It uses tangible blocks to control the virtual main character's actions; it can move forward, backward, left, right, pick up objects, and jump over obstacles. Fourth, we showed a fully tangible environment with DASH controlled by PUZZLETS, a setup where sequences of blocks can be composed on a tray.

Analysis
We used affinity diagrams [23] to analyze and categorize data from the focus group. First, we analyzed the post-its written during the session, and completed them after listening and discussing the audio records. Two researchers iterated on the relationships and categorisation of the data, which was then presented, discussed, and refined with the entire team.

FINDINGS
Educators started the session with a mixture of interest and caution. Although they perceived benefits in a future inclusive programming classroom, their expectations were low. However, during the presentation of the environments, they became more enthusiastic, and the feedback became actionable. We report the categories that emerged from our analyses on the qualities and opportunities to use robots, blocks, boards, maps, and their relationship with child development and learning.

Robots
Robots are attractive and engaging for children, and relevant to learn complex concepts [4, 8, 44] such as CT. The educators highlighted the importance of using a robot and its physical and socio-emotional features. All educators preferred DASH

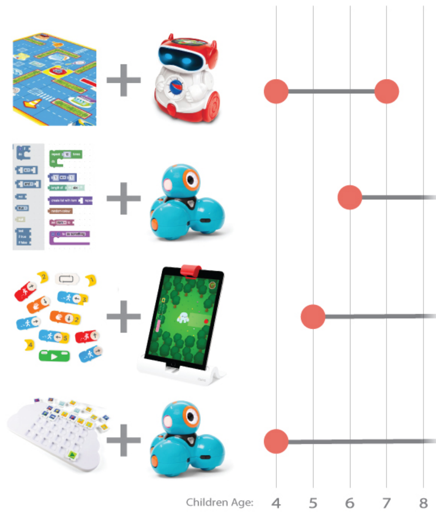

Figure 2. Environments used in Study 1. From top to bottom: robot DOC and map; robot DASH and BLOCKLY App; Osmo Coding AWBIE App and blocks; and robot DASH, PUZZLETS blocks and tray.

over DOC as it contained relevant physical features: aesthetically pleasant, warm colors, *affable spheres*, ergonomic to touch and *cute*. In contrast, DOC was seen as less pleasant and perceivable, both visually and physically.

> "I think [Dash] is better ergonomically for younger kids to touch [...] circles, because it's a shape that they most identify with." – SNE2

Socio-emotional affordances were remarked as important for successful interaction with the robot. Examples were friendship, calling by the child's name, and positive reward. Educators also highlighted the benefit of enabling the personalization of the robot with accessories. These could be made of low-cost and children-friendly material as play-doh, Lego bricks, and adhesive tape. Educators also suggested that the robot's lights should be used with parsimony to reduce overstimulation, avoiding possible episodes of epilepsy. DASH has different lights, but they are programmable. This fact enables educators to customize the robot accordingly to children's needs.

In terms of *sensorial feedback/ integrated representation*, the robot should provide feedback on its actual position and feedforward its actions. None of the robots accomplished that. Educators pointed out that the robot should speak loudly and guide the children in the activity, providing audio feedback of the actions it is performing. The robot could also give audio feedback to announce its location and orientation on the map. One quality of DOC is that this robot announces a goal (verbally indicates where to go in the map), and it announces when the proposed goal was reached (or not); educators found it very useful. Conversely, DASH does not give any audio feedback regarding its actions, location, or success.

Overall, the educators stressed the relevance to add tactile feedback to the robot and its path. One suggestion was to attach accessories to improve traceability, e.g., "a 3D pen that would leave a trail of the robot's movements" – SNE3.

Blocks

To program the robot, educators unanimously stated that the use of tangible blocks would be the best option. However, neither AWBIE nor PUZZLETS blocks had enough tactile information, preventing visually impaired children to differentiate them. Educators highlighted the importance of blocks being light and small, as PUZZLETS blocks, to stimulate the development of their fine motor skills. The AWBIE blocks especially attracted them due to the magnets that ease their composition; and due to the intuitive design of the direction blocks in which the arrow's direction can be easily changed.

> "It will be enough to have just the [arrow] head" – SNE2

Tangible blocks raised a series of opportunities by the educators, such as the possibility of augmenting their *sensorial feedback/ integrated representation*. The tangible blocks could have an audio button to announce their action or Braille inscriptions. Blocks could also vibrate or emit a sound at the time of their execution to facilitate debugging. The drawings illustrating the block's action should be simple and in 3D or embossed. They also suggested using easily-recognizable pictures for haptic perception. For example, the use of an arrow to indicate movement direction would be easily recognizable. In the same vein, educators suggested the usage of Picture communication symbols (PCS) used primarily for deaf children. However, it was stressed that these tactile cues should be carefully designed. One educator explained the importance of having just the minimum tactile information as possible, as "too much may be detrimental for recognition" – SNE1.

Boards

Educators suggested that having a confined space to order instructions would facilitate their programming activity. It would also release cognitive load, leaving available resources dedicated to strengthening the learning process. Educators observed that the fact that the board or tray defines a personal workspace allows the children to work with both hands at the same time, and helps in structuring the coding blocks:

> "if we have a confined space it will be easy [to debug]" –SNE1

Using a board brought back a series of possible opportunities to incorporate *sensorial feedback/ integrated representations*. The board could have tactile or auditory cues or Braille inscriptions, indicating the execution of each block. The size of the board is important to facilitate the use of both hands. This would enable free play, and faster usage of the system as all the information is integrated into one object - the board. This board could also include space to store and organize all blocks, even the ones not in the current program.

Maps

Educators valued the use of a map (e.g., with DOC) to allow children to explore the space, bounds of the workspace, and promote orientation skills. The map could be of a real location, known to the children, for example, their school or neighborhood. Educators mentioned the possibility of integrating *sensorial feedback/ integrated representations* in the map. The map should have tactile cues or Braille inscriptions easily recognizable by touch.

Table 2. Children in Study 2. Table indicates the workshop group, age, grade, sex, visual impairment, and mental or physical comorbidities.

		Age	Grade	Sex	VI	Comorbidity
G1	P1	5y10m	1st	F	Low-Vision	GDD
	P2	7y6m	2nd	M	Low-Vision	-
	P3	6y11m	2nd	F	Low-Vision	GDD
G2	P4	9y8m	3rd	M	Blind	-
	P5	9y1m	3rd	M	Low-Vision	GDD, ADHD, poor laterality, and compromised hand-eye coordination
G3	P6	11y1m	4th	M	Partially Blind	-
	P7	10y5m	4th	M	Low-Vision	-

VI: Visual Impairment; G: Group; P: Participant; GDD: Global Development Delay; ADHD: Attention Deficit Hyperactivity Disorder.

Overall Perceptions

This study enabled us to identify key aspects for an accessible programming environment. Educators were motivated about the use of a robot as they found it engaging for activities. The robot should have feedback and feedforward information, enabling children to be aware of its actions. The use of tangible blocks was considered the most adequate. To make them accessible, they should have further sensory representations, such as auditory or tactile cues. To conduct programming activities related to spatial perception, it seems opportune to use a tactile-rich map that could foster spatial perception, orientation, and other-domain (e.g., geography) learning activities. The usage of boards was also praised, albeit the awareness that it could restrict collaboration or impair space organization.

STUDY 2: EXPLORING PROSPECTIVE APPROACHES

The solutions presented in Study 1 were all inaccessible. However, they all showed to have qualities that could be leveraged in an accessible programming environment. Educators showed enthusiasm in possible adaptations of such approaches and fantasied about their usage and possible benefits in situated classroom experiences. In this second study, we adapted a solution to include a set of qualities identified in the previous study and engaged visually impaired children in a programming workshop with spatial activities. The findings reported here emerged from our observations that were latter validated in a follow-up focus group with children's educators where we showed the video-recordings of the workshop.

Participants

Seven visually impaired children from the same school of Study 1 agreed to participate (Table 2). To fine tune our analysis, we later conducted a focus group with 6 SNEs (same as in Study 1), a new SNE (SNE5) and IT instructor (IT3).

Bespoke Study Probe

Informed by Study 1, we set out to adapt a solution that would feature tangible and audio-rich blocks, a recognizable tactile map, and a robot with augmented physicality, feedback and feedforward mechanisms (Figure 3).

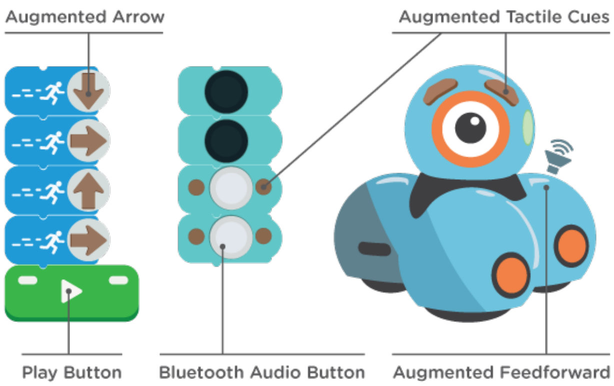

Figure 3. Tangible and audio-rich blocks and the robot with augmented physicality, feedback and feedforward mechanisms.

We used DASH due to its current usage in school settings and because educators praised it. This robot already integrated rich tactile cues, but to make it more obvious, we also used felt pads cut as eyebrows and placed them over the eyes, to augment its front/back asymmetries. We also artificially added audio feedback and feedforward to the robot's actions.

We also followed the educators' preference to use the AWBIE blocks as the programming blocks. We selected three types of blocks: the Play Block to run the program; Action Blocks that instruct the character to perform an action (e.g. move, dance); and Direction Blocks that indicate movement direction. The Play Block had enough tactile information, thus no changes were made. On the other hand, the Action and Direction Blocks needed strong tactile cues. We added a Bluetooth button with audio feedback to the Action Blocks, which reported its action when pressed (sound came from a secondary device). To distinguish between two different Action Blocks, we added different round tactile stickers and used buttons of different colors. For the Direction Blocks, we augmented the flat arrow with a 3D arrow made of a felt pad; it could be rotated as the original AWBIE block.

We also added a map to the goal-directed spatial activities. It consisted of 6 EVA foam tiles of 33 x 33 cm with two different colors (Figure 1). Each tile represented 1 unit, and colors were interleaved to enable children with low vision to distinguish them. Tiles union was perceived by touch, and children were able to count how many units composed the map.

Children would place the tangible blocks on the table in the order they wanted the robot to perform the actions. We used a Wizard-of-Oz methodology to respond accordingly to the blocks. One of the researchers would keep copying the block sequence to the BLOCKLY App, which instructed the robot to perform the actions. Only blocks attached to the Play Block, and after pressing Play, were executed.

Procedure

We divided children into 3 groups, selected by their educators according to their age, grade, and cognitive abilities. We repeated the workshop activities for each of the three groups, and sessions were video-recorded. We started with a discussion about robots: what it is, what it does, if they have ever touched one, how does it work, if it is autonomous or needs a human to command it.

Then, we divided the workshop into two types of activities (Figure 4). First, we started with unstructured exploratory activities *physically led* by the children, where children were free to explore the robot while turned OFF as well as when turned ON. We introduced the blocks and allowed them to freely explore the causal relationships between the blocks and the action performed by the robot. Next, activities were goal directed, where children had to complete spatial activities in a map placed on a table (Figure 1). At the end of the Workshop, we debriefed the children about the programming activities and the robot. Finally, we asked if they were interested in playing with the robot in the future and why. Each group session took approximately 30 minutes.

Analysis

We performed a reflexive thematic analysis [9, 10] of the videos from the workshop with children. We followed a mixed coding approach, where we designed the first codebook from our theoretical background and knowledge, and inductively enriched it with observed codes. To validate or refute our interpretations, we went back to educators and presented video clips covering all the phases and activities of the workshop - we removed portions with no activity or where no new behaviors were observed. We invited educators to interpret and discuss clips. Our aim was to enrich our analysis with interpretations of children's behaviors by those who work daily with them.

FINDINGS

Activities in Study 2 were characterized by novelty and a feeling of excitement. Our findings indicate that, from a perspective of physical access, visually impaired children could be having similar spatial training activities as their sighted peers. Such findings should be interpreted in light of the limitations akin to a short session, with a limited set of spatial activities and CT concepts. Still, different behaviors and opportunities emerged and were discussed with educators.

Exploring the Robot

Preconceptions and First contact

This was the first time these children ever touched a robot. One of the educators mentioned that the unfamiliarity with robotic nomenclature is age-related; while younger participants are less likely to have been exposed to robots, and hence, less likely to talk about it and understand what it is, older ones were much more acquainted with this technology. Older participants stated that a robot is capable of doing things, is programmable by humans, or controlled by remote controls.

We started with unstructured exploratory activities to promote physical exploration. Children immediately examined DASH by touching its head, eyes, body, eyebrows, and moving it forward and backward on the table.

> "I noticed that the first big contact is physical, it's exploratory. It is moving the object and not expecting it to

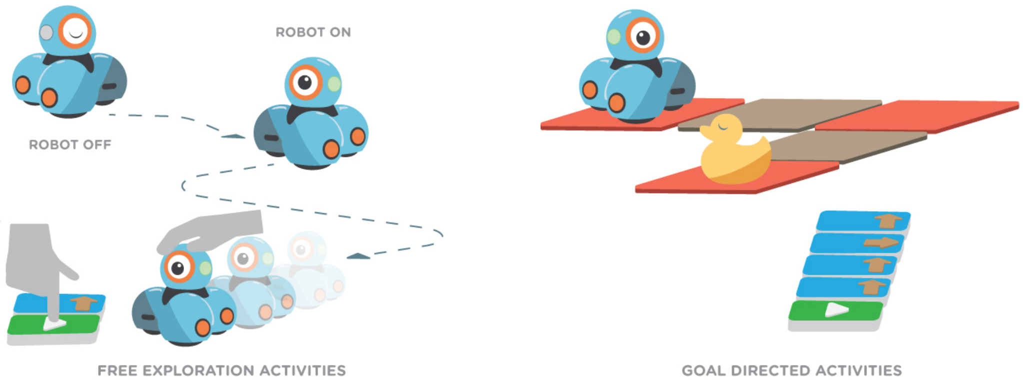

Figure 4. Type of activities in Study 2. Children started with unstructured exploratory activities *physically led* by them -left panel. Then, we moved to structured and goal directed activities where children had to solve spatial tasks in a map involving the robot and the target (duck) -right panel.

> do things. It is exploration, the discovery of the object. Almost smelling it..." – SNE1

Children differed in their approaching strategies, according to their age. Younger children explored spontaneously and abstractly, not expecting too much from DASH. They moved it and tested the robot's mechanics and physical limitations. Older children made a more conscious and concrete exploration. They sought to understand the morphology of the robot. These children also tried to understand how they could use DASH and what to expect from it by pressing on a specific part of the robot, or by using a specific block (e.g., using a walk forward block to see the robot's reaction).

Agency of control

Children were verbally encouraged to switch ON the robot. Educators were amazed by children's motivation and interaction with the setup and they justified such enthusiasm, in part, with the agency of control in switching ON the robot by themselves. Additionally, the robot reported which action it would immediately execute (e.g., "I will walk forward"). Being able to anticipate DASH's actions gave children a sense of control and safety, which also led to a greater interest, ease, and speed in the understanding of the setup and concepts.

> "[...] anticipation of action is very important. It offers them more security. Knowing what will happen, to some children, is very important, and with the repetition of the information, they feel safer." – SNE4

In general, children also had the perception of agency of programming the robot. They felt that the blocks they used were the commands to program the robot. Occasionally, there were breakdowns with the Wizard-of-Oz during the activities. One of the most notorious problems was when children gave multiple orders in a row, making it impossible for the Wizard to timely react. Only one child suspected that the robot was controlled by one of the team members due to its lack of consistency (between pressing the Play and the robot's action) and slow response of the robot, and kept challenging the setup.

Robot anthropomorphization

Anthropomorphization is the tendency to attribute human characteristics, emotions, or intentions to non-human entities. Children, when compared to adults, show this bias more naturally raised and generalized. As such, children are more prone to anthropomorphize and establish an affective relationship with robots [11]. We observed this phenomenon in specific behaviors: children talking to the robot, kissing it, and putting the ear near to listen to it. Besides, children would turn the robot towards them so they could be face to face. One child, after covering one eye of the robot said "He cannot see" – P6.

In our experiment, we had two children (P1 and P3) with low vision and global development delay associated with cognitive impairments. Such impairments can represent an added challenge in performing the activities [18]. One of them, P3, was the one who often kissed the robot. Her affective relationship with the robot frequently prevented her from solving the activities or from using the blocks. However, when the researcher asked P3 to move the robot to go to his friend, the duck - i.e. the target-, the attitude changed. In the child's perception, a new emotional motivation flourished between the robot and the duck. P1 enthusiastically guided the robot to the duck, using the blocks. This contrasts with the first time P1 verbally ordered the robot to "go to the duck", expecting success by just announcing the target to the robot. After some guidance, she was able to program. However, it was not clear if she understood the system or the concept of programming a robot.

It may be suitable to have environments that are flexible in the way the robot is commanded and may evolve: the robot could be commanded by a voice user interface in the early stages [20], or for children with cognitive impairments, and only later include blocks as the programming mechanism.

Integrated feedforward

Children listened to the robot verbally anticipating its actions (e.g., "I will walk forward", "I will walk to the right"). This representation of the robot's movement worked notably well.

> "I think it's fantastic because there are more channels of information to the brain and everything helps. It is much faster. [They] know what's going on, [they] don't have to put [their] hands to know where the robot is going." – SNE1

In addition, educators suggested that feedforward could be further enriched. It would be useful if the robot could detect the map, or the target, and verbalized it. The integrated audio representations in the robot could provide its actual position, next action, and the location of the target in the map, concerning the position of the robot.

They also suggested integrating sounds or music in the integrated representation of the robot. For instance, when the robot accomplishes the task, he could make a specific music or sound (e.g., “yoooh") or, when he fails, emit a different sound. Another suggestion concerned the usage of music to indicate specific directions along with the feedforward speech. However, it was also stressed that the use of other audio cues should be carefully designed in order to avoid cognitively overload children and jeopardizing learning.

Exploring the Blocks

Play block

The Play block allowed using blocks anywhere on the table by providing a clear anchor for the program. The working area for visually impaired children is very relevant, as they are used to dedicate part of the table to prepare materials and to perform epistemic actions. Such actions like manipulating physical objects may facilitate cognitive operations needed to perform a specific task.

Direction blocks

Children easily perceived the 3D arrow symbol and quickly associated the arrow with the direction the robot had to take. In one group, when the researcher said “if the arrow indicates this side", P4 finished the sentence: “the robot goes that way". Educators were excited by their understanding of right and left concepts.

> "this [move a robot in a map with direction blocks] will really help them to get that [laterality] notion." – SNE5

Laterality conceptualization is very important for visually impaired children and is related to spatial cognition, orientation, and navigation skills. The use of spatial concepts could also motivate children to move and explore the space.

Action blocks

Action blocks led to a less intuitive understanding of the auditory representation. Children pressed the button to listen to the feedback. Simultaneously, they were expecting the robot to do the action at the same time. For the younger children, it was difficult to understand the difference between the robot feedforward audio and the sound emitted when pressing such blocks. Children had difficulties understanding why the robot did not dance if they pressed the “dance” button in the block. One aspect that may have also added confusion was that the block’s auditory feedback came from a third source (neither from the block nor from the robot).

Attaching the blocks

Educators mentioned that the connection of the blocks made through a protrusion was sufficient. Also, the magnet in these blocks played a very relevant role to ease the task of attaching them. Interestingly, Direction Blocks were attached differently compared to Action Blocks. Even after explaining, children often tried to stack blocks as Legos. The Play Block button’s relief made some children assume that the pieces fit vertically, trying to stack them up. We did not observe this fitting affordance in the Direction Blocks. Direction Blocks were frequently joined from the side, above or below the Play Block. After an explanation, they had no difficulty in understanding it. On the contrary, with the Action Blocks, they continued to follow the affordance of the audio button for a little longer, until they got used to assembling it with the Play block.

Integrated feedforward

The integrated representation in the blocks served to inform children about its actions. However, we found that, if we have a robust haptic representation or an intuitive haptic affordance [13], the audible feedforward information may lose relevance, although further studies are needed to explore these aspects. The fact that the sound did not come from the block itself but from a third device was confusing for the children. Educators reinforced that the affordances designed should include symbols that are already recognized by the children. They also insisted on integrating Braille, and 3D or augmented 2D, to inform about the actions the blocks represent when designing new actions.

Emotional and Embodied Experience

We observed an emotional and embodied experience with the setup, mainly with the robot. All the children were happy and enthusiastic to play with the robot, and their bodily expressions demonstrated interest and pleasure. In the beginning, they were surprised, and when the robot was turned ON, children exhibited more enjoyment and happiness; surprise also increased as the system showed something unexpected. Their body posture, inclined to the table to be next to the robot, ears inclined to the robot location, and they rapidly grabbing and moving it to start the activity, denoted interest, and satisfaction.

Children were curious about the effects of the blocks in the robot and showed great excitement (operationalized as when children laugh, scream of joy or applaud) when the robot collided, reached the duck, talked, and danced. For instance, children applauded and laughed when they programmed the robot to make his way to the duck. One educator mentioned, about P5, a child with Attention Deficit Hyperactivity Disorder, and a severe global development delay.

> “The speed with which he has learned, and the degree of satisfaction. This posture...he must have a huge ego now, right? For him, this was fast learning." – SNE1

We also observed, in a few instances, that children felt annoyed, bored, or neutral when others were accomplishing the task. This was mitigated throughout the workshop by having short activities, so the child could collaborate or wait a few minutes. Children may have created an emotional bonding with the robot; especially the youngest ones who had a stronger tendency to anthropomorphize the robot since it talked and moved. Their educators reinforced our observations that children created an affective relationship with the robot:

> “Amazing. I think it was affable to everyone. No one showed fear, not even with the light or noise. It was an affective relationship that was established." – SNE2

Educators were amazed by children's interaction with the system. The fact that they were learning to program the robot with pleasure was promising for future learning endeavors:

> "I think the most amazing thing is to see their joy when they complete the activity"– IT1. "It was positive. Even in the initial expressions they were already interested [..] I think they were very happy to be there" – SNE2

In the debriefing with each group, children stated to have liked the robot, that it was *cool*. They were enthusiastic about having a map and with the fact that the robot talked and danced. Three children referred that the robot was slow to react, as the characteristic that they liked the less. Whereas for the younger kids, this was not so evident, for the older ones, it was obvious: they wanted a faster response. They also mentioned what they would like the robot to do: fly with metallic wings, make videos, music, or take pictures, which seems to be influenced by what other technological devices already do (e.g., drones).

Embodied experience

The workshop was organized to evoke different embodied experiences and interactions between the children, the blocks, and the robot, incrementally. We started with free exploration to build knowledge through experience, and then we moved to more structured activities. The structured and goal-directed spatial activities are cognitively more demanding, and to mediate this factor, a self-paced session structure, and step by step instructions were applied in such activities. This format helped children to understand the activities and, consequently, facilitated a sensation of empowerment as they were able to perform the task and command the robot. One educator remarked:

> "the instruction was very well given. It has a lot to do with how you give the information. Step by step. It was sequential. So his reasoning was not imediate, it was oriented. And that makes it successful." – SNE1

Children used their bodies to explore the table where the map was located, to move around the map and the target, to indicate to peers where the target was, or to indicate how many units constituted the map. Such embodied conceptualization transfers from the bodily to the abstract plane which may facilitate learning [2, 17]. To ease physical embodiment, the dimensions of the map and path should be known to the child and explorable. Their knowledge about the spatial configuration of the table enabled an easier understanding of the map units.

> "they knew the size of the table and they all explored" – SNE1. "they were aware of the size of the map and how many units" – SNE5

Educators remarked that the distance of each robot *step* should be explicit to develop a mental model about the blocks and the robot moves. In our activity, the robot moved the distance of one unit of the map, so children did not have to think about distance but only in *steps*, which is cognitively less demanding.

Embodied experiences can be potentiated by associating the tangible environment to world experience or to previously learned knowledge. Educators remarked that real and embodied situations facilitate the understanding of spatial activities:

> "For younger kids [make them do] two jumps forward, one to the side, and then the cognitive map is there. Then, try to make the transfer. If I was going to do it, that's how I would do it" – SNE1

Designing activities with real spatial explorations, where children can apply abstract concepts in real life, can ease learning and be very motivational. One IT illustrated with an example:

> "DASH goes on a mission to try to, as if he belonged to the fire department, save people in a building. Because in this situation it is dangerous to make this reconnaissance [by a human], they have to program DASH to do it. They have to understand why they are programming the robot and why the robot is important. Create real situations. Give meaning" –IT3

Educators suggested that activities could also teach children about their environment. They suggested to use different maps in the activities, such as a school or residential areas, or learn about unknown information, such as cities or science themes. Maps would need to have tactile cues such as Braille, reliefs, 2D iconic representations or different textures. On the other hand, representation of the robot steps could be a plus; children would have the opportunity to touch the path already travelled by the robot which could facilitate debugging.

Collaboration

We did not design the activities with the goal of fostering collaboration. However, collaboration emerged naturally within the groups. Tangibles are known to support rather than require collaboration, engaging children in playful learning [29, 39, 53], making children more prone to divide, explore and share supporting collaborative actions [1, 2, 22].

All children wanted to play, manipulate and program the robot and this had an impact on the collaboration with their peers. Because children wanted the robot for themselves, we used sequential turn-taking as the learning strategy so each one of them would have the same opportunities. We observed collaborative actions, such as, supporting other's learning, instruct partners and reinforcement. It was common to observe children helping each other by verbally or bodily communicating where should the robot go, or through which cells the robot should walk to arrive at the target. Another way of supporting a peer was by manipulating the blocks that should be used to perform the activity, such as correcting the blocks or correcting the arrow direction. Frequently, children followed the recommendations of their peers. Learning was reinforced through dialogue or embodied behaviors as *a priori* corrections, or by being helped in debugging. These corrections reflect that they have learnt how to command the robot and they were able to indicate to their partners the correct solution. In addition, "the second always performed better than the first. This is inevitable. They learn from the mistakes" – SNE2.

Success was shared among the group by screaming with joy, applauding or looking to each other as perpetrators of success. We also observed a breakdown in collaborations when the peer was taking too long to perform the activity. Educators suggestions to foster collaboration included giving different types of blocks to each child or group so they would be forced to find a solution together. Another suggestion focused on competitive-based collaboration: having groups of children competing to arrive at one solution as fast as they can. However, competition should be carefully designed enabling children with different abilities to be equally able to solve the activities. In addition, younger children may have not finished developing skills needed to succeed in competitive activities [42] which may harm their learning. Young children are more play-oriented and centred in their experiences, compared with older children (since 8 years old). Conversely, older children may benefit from competitive-based activities, where competition serves as a learning facilitator and motivator [42].

One way to explore collaboration would be to first ask children to give instructions to other children as if they were a robot [33]. This would help them acquire taking other's perspective and understand how the instructions inform robot's actions. In addition, they could verbalize how they build such instructions and program to their peers, which also reinforces learning.

Conceptual Knowledge and Learning

Programming knowledge in children has been identified with two key indicators [15, 43]. One is the ability to match a programming command with its outcome or action. All children, except one, reached this key indicator; they were able to understand the blocks' functions and the output they generated in the robot. In addition, they also understood that the robot executes the sequence if they press the Play Block's button, and not before. Educators were surprised with the proficiency and understanding of this abstract concept in the first contact they ever had with a robot and tangible programming.

The second key indicator was only achieved by older children and one of the youngest. It relies on the ability to create a program that uses the correct commands in the correct order. They had difficulties in arranging blocks, and to order sequences from the bottom to the top, as in understanding that the order starts from the first block attached to the Play Block.

Another difficulty was to understand that the robot executes the complete sequence attached to the Play Block every time the button is pressed. Children had a tendency to press the Play button several times to execute all the sequence. This is also coupled to the lack of understanding that they cannot change blocks on the fly: they have to wait until the robot completes all the sequence in order to re-arrange the blocks.

We observed significant (epistemic) actions to reinforce learning - actions users do to change the environment while searching for possible solutions or strategies. Epistemic actions are necessary to offload cognitive processes that are still abstract or difficult for children at these ages. The use of tangibles increases the possibilities to perform a variety of epistemic actions important to deepen and integrate knowledge or develop new understandings of the functionalities [1, 3]. Although such actions are not performed to directly solve the task, they are needed to establish or change cognitive operations related to successfully completing the task (e.g., make a sequence before attaching it to the Play Block; prepare the arrow's direction; ; compare the direction of the Block's arrow with the direction of the robot). For instance, the orientation of the sequence of blocks sharing the same referential between the programming and execution plane, seemed to be a highly relevant action to support children in their learning and perspective-taking.

Cognitive Development and Spatial Cognition

The development of abstract thinking is related to the way children associate and interpret concepts [17]. Younger children rely more on concrete thinking, physical symbols and representations [14, 34]. We observed that children were more focused on the robot rather than on its action. Conversely, older children relied more on developmental abstract thinking:

> "There are exploratory but more intentional movements, to see where it moves. They [older ones] already have a different intent" – SNE1

Older children were more concerned with the action of the object (blocks or robots). For example, debugging was often observed in older children while younger children were more prone to trial and error processes.

While children grow up, they become better in logic-based causal reasoning and perspective-taking [14, 34]. Perspective-taking is the foundation for many higher cognitive skills, especially for social skills and theory of mind, and is developed systematically. It is considered a milestone in early childhood development of cognitive structures, together with object permanence, symbolic play, and first words. We were able to assess this skill in the last activity. The robot had to move 2 units forward, then turn (move 1 unit to the right) and then move 1 unit forward. Once the robot turns, the reference frame of the child and the robot are not the same anymore (Figure 4). Children needed to take the robot's perspective to get to the target and properly solve the task.

Spatial orientation was emergent in such activities. Spatial orientation integrates perceptual and cognitive learning and requires conceptual development such as body scheme, spatial and time cognition, as well as conceptual understanding of objects [51, 41]. The type of setup as the one we used could improve children' spatial cognition, mental rotation and navigation skills. It is important to relate these spatial concepts with their position, body and environment, to build laterality conceptualization among other spatial concepts as direction and orientation. Understanding of spatial concepts is crucial in visually impaired children so they can navigate, orientate and build more abstract reasoning [51, 41].

DISCUSSION

In this paper, we contribute with an important process for understanding the necessary qualities of a spatial programming environment along with the reactions of the educators and students. We report findings that integrate children's abilities and needs and their educational environments that are helpful to other researchers and practitioners working in this area.

Our approach focus on programming a robot in activities that are predominantly spatial and non-visually more demanding. Previous approaches, such as Storyblocks and Project Torino [21, 45, 32] use tangibles but activities consist of auditory stories or music, without a tangible output as a robot performing actions. Blocks4all [31, 24] uses a touchscreen device compatible with VoiceOver to spatially move the robot. Their studies showed that visually impaired children struggled with the activities and more work was needed to reduce the demand associated with these challenges. We sought to bridge this gap. One clear difference is our focus on tangibles, that are recognized to reduce cognitive demand. Because thinking is grounded on motor actions, the manipulation of blocks and gestures associated activate embodied processes that may serve to integrate conceptual knowledge [46]. Such perceptual experiences may enhance the development of spatial skills, such as orientation and navigation, imperatively important in the life of visually impaired children.

Designing accessible environments. Our studies highlighted that it is achievable and affordable to promote inclusive tangible robot-based programming environments through spatial activities. To achieve this, we explored together with IT and SNEs, the required sensory integrated representations they should feature to be accessible. The augmented physicality of robots, blocks, and maps showed to be promising to provide a layer of inclusion to visually impaired children. Similarly, increased and consistently designed (audio) feedback and feedforward mechanisms are pivotal to potentiate concept acquisition and enable a faster learning curve. The layers added to include visually impaired children, most with multiple comorbidities, seem to be amenable to most of the available tangible programming environments.

Reinforcing situated classroom activities. Educators were particularly avid to find overlaps between the CT concepts/activities and what they already try to foster for the development of their younger students. They saw tangibles and every tactile cue as a reinforcement for children's perceptual abilities, they saw maps as a way to develop spatial abilities, they saw the programming space, with trays or not, as a way to promote structure and organization, and they saw the robot as a motivating artefact that could easily reinforce causal relations and mappings.

Educators also identified opportunities to explore other disciplines (math, science, geography) by leveraging programming environments. For example, the use of maps and grids is already common in several activities, albeit differently between sighted and visually impaired children. Educators saw an opportunity for inclusion in the adaptation of these other learning activities to be performed through a programming task. One educator remarked:

> "programming and robotics, in the middle school with sighted children, everyone has a map. Now, we have to know: can we do that with these students?" – SNE5

The caution in this educator's words is advisable. It is certainly a challenge to reform activities to be done differently and to be inclusive. Their opinion reinforced that programming environments, given their ongoing establishment, could be tools of inclusion, rather than exclusion.

Fostering collaboration. Collaboration emerged during the activities with children. Educators proactively saw interest in these interactions. When discussing how collaboration could be promoted, different elements of the setup were dissected.

Small boards and trays were seen as valuable in many ways but detrimental for collaboration unless there could be different boards for each child while contributing to a common solution. Voice was seen as a plausible means of initial programming that could accommodate further collaboration between the children. Tangible blocks were confirmed as enablers of collaboration, allowing children to share, explain, explore and divide, among other actions [36]. The same applied to the robot that could be felt, listened, inspected and followed.

Regarding the space for the activity, i.e. with the map, the opinions were divided between having it on the floor, in a wider space, or on a table. Using a larger space could be relevant, e.g., to promote spatial concepts, but could also jeorpardize sharing the *programmer* role between children. One of the ideas discussed to mitigate this challenge was to also enlarge the programming area as well, e.g., using the entire vertical whiteboard as the programming area where children could contribute to a solution.

Collaboration was also discussed within the scope of a mixed-ability classroom. Educators found interest in fostering collaboration by creating activities that attribute different roles to different actors, that could be valuable for the learning task but also to promote closeness and awareness.

LIMITATIONS

Although we discuss inclusive classrooms and performed studies with educators that work in such contexts we decided to focus solely on a group of visually impaired children, without including their sighted peers, for now. Another limitation concerns the fact that we did not assess CT concepts such as loops or conditionals, and our discussions with educators were only lightly informed by such future challenges. The study was limited to one session, and children's interest might be subject to a novelty effect.

CONCLUSIONS

Several tangible introductory programming environments emerged in the last few years. Their lack of accessibility gave origin to attempts to create custom solutions. We differ from prior work by taking a moderate stance, where we sought to preserve the qualities of existing spatial environments, and decades of research and practice, for sighted children; and take careful steps towards inclusion with SNEs. This approach enabled us to produce findings that are informed by theory and practice, and attainable. We expect that researchers, developers, and educators can build on these findings to develop or tinker current solutions, and navigate towards situated inclusive classroom activities with children with mixed abilities.

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SELECTION AND PARTICIPATION OF CHILDREN

The research protocol was approved by the Ethics Committee of *Faculdade de Ciências* - CERPDC - and authorized by School directors and the Special Needs cabinet who oversaw the entire process. Parents/legal tutors signed consent forms to allow their children to participate, which included a full description of all activities, analysis and future usages. All children assented to participate. Activities were designed for a positive/playful experience and a SNE was present to give children more security. One participant had a severe GDD and was very anxious at the workshop. Jointly with their educators, we decided to not include him in the goal-directed activities, to prevent him from struggling. One researcher was always with him and with one robot so the child could be part of the activity.

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