An Approach Based on Learning by Teaching to Support the Vertical Alignment of the Educational Robotics Curriculum

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Abstract: Vertical alignment delivers a smooth, organized curriculum. We explored an approach to apply Learning by Teaching (LbT) to support the alignment of the educational robotics curriculum and, in turn, strengthen the connections among different age groups to foster digital and social inclusion. We applied LbT in the context of teaching an introductory course in robotics in a high school, and we summarized our experience in a report that analyzes two relevant aspects: a) Understanding whether LbT supports teaching-students in learning robotics concepts and b) outlining the effectiveness of LbT for interactive activities targeting younger children during Science Festival. The observations reported in this work show that teaching-students are a relevant support for actual instructors; moreover, their activity offers several advantages, including enhanced engagement and active participation, which contribute to improved comprehension and knowledge transfer.

1 INTRODUCTION

Vertical alignment delivers a smooth, organized curriculum that prepares students for the next grade or level. For example, every teacher may introduce different educational robotics elements within a course (e.g., hardware or programming languages); however, the basic structure focuses on a learning area for each level. When a curriculum is vertically aligned, the transition between school years becomes more straightforward: the previous year's class will have provided all the necessary vocabulary, information, content, and resources to prepare students for the following year. Therefore, vertical alignment, for example, reduces the time needed to review previous content and reduces the gaps in the learning process.

Learning by teaching (LbT) is an educational approach in which individuals enhance their learning and understanding of a subject by teaching it to others (Cortese, 2005). By engaging in teaching activities, the sole process of being passive recipients of knowledge is shifted, and learners take on the role of mentors to share what they have learned with others. In LbT, teaching-students define their methods and teaching approaches, implement them to teach the topic, motivate, and ensure that the subject is understood (Debbané et al., 2023; Gartner et al., 1971; Duran, 2017). Therefore, LbT can effectively teach key 21st-century skills (Aslan, 2015). Learning starts during the preparation phase and is reinforced by teaching (Aslan, 2015). Reflection during and after the teaching process helps evaluate the comprehension of concepts and the teaching methods (Chi et al., 2001).

This work aims to increase the vertical alignment of the educational robotics curriculum that, starting from elementary school (6-10 years), accompanies children in their personal growth and eventually serves as a pivot to evolve from learning-student to teaching-student through LbT. Using LbT supports an intergenerational program and the subsequent strengthening of connections among different age groups and promotion of experience sharing (Phang et al., 2023), which, in turn, fosters digital and social inclusion, i.e., one of the critical success factors of smart cities/villages (Shin et al., 2021).

To pursue our objective, we explored an approach to apply LbT in the context of teaching an introductory robotics course in high schools: teaching-students learn robotics concepts and create a set of flip cards as teaching material for an interactive expe-

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rience to let children move their first steps in robotics. As a context for the interactive experience, we chose a Science Festival based on the assumption that these events attract a broad audience that is curious and motivated to learn. We summarized our experience in a report to analyze two relevant aspects:

- Understand whether LbT benefits teaching-students in learning robotics concepts.
- Outline the effectiveness of LbT for interactive activities targeting younger children during Science Festivals.

The strategy and activities described in this paper include: (1) Design a set of robotics activities addressed to a non-expert audience participating in a Science Festival in a mid-size city, in which the volume of participants makes the involvement of many instructors essential; (2) Identify a team of students to serve as teaching-students, leveraging the robotic concepts they gained at the school; (3) Work along with teaching-students in the process of creating the teaching material. In particular, teaching-students created flip cards to facilitate large and heterogeneous groups of participants (Fronza and Pahl, 2019); (4) Teaching-students peered at younger students during the Science Festival. Through the success of the activity and our observations, we outline how the teaching-students successfully learned the robotics concepts, deepened their understanding while teaching, and exercised their soft skills.

The rest of the paper is organized as follows: Section 2 investigates the state of LbT; Section 3 describes the setting and fundamentals of our experience report; Section 4 discusses results and lessons learned; and Section 5 establishes directions for future work and draws conclusions.

2 BACKGROUND AND RELATED WORK

2.1 On Student/Mentor-Led Learning

Student-led and mentor-led learning has emerged as relevant topic for the research and practice of education. With the many paradigm shifts in education that came with and after the pandemic emergency, having a solid support network became paramount in education processes. The research found that peer mentoring positively impacts motivation, studying behavior, and exam results (Hardt et al., 2022). A comprehensive literature survey discusses several concepts encompassing mentor-led learning, including reciprocal teaching, peer-assisted tutoring, and self-explanatory teaching (Biswas et al., 2005).

Learning by Teaching (Gartner et al., 1971) is a pedagogical method where *teaching-students* teach to *learning-students*. The benefits of LbT include more effective learning of concepts, higher participation, better learning satisfaction, development of teamwork skills, and promotion of higher-order thinking (Debbané et al., 2023). Furthermore, studies have shown the better performance of students who learned material with the expectation that they would be required to teach it (Benware and Deci, 1984). While peer tutoring aims to educate both tutor and tutee, LbT focuses on the teaching-student's learning (Debbané et al., 2023).

A mentor-led environment creates a relationship in which a more senior individual provides guidance and support to junior members. As a main advantage, the peer-to-peer connection eases knowledge transfer and harnesses social support behaviors, resulting in positive perceptions of the relationship's effectiveness and underlying trust (Trainer et al., 2017). Moreover, learning-students are more at ease discussing sensitive topics such as assessment and room for error with a colleague rather than a member of a formal teaching staff (Iacob and Faily, 2020). Nevertheless, some commonly identified shortcomings are that learning-students might question the accuracy of the information provided by the teaching-students, and ask for validation from the teaching staff (Iacob and Faily, 2020). Moreover, this structure requires several personal traits, at the risk that peers might not take the knowledge transfer session seriously (Aslan, 2015).

Student/mentor-led learning unleashes a critical potential for both sides (i.e., teaching-student and learning-student). For example, in intensive educational experiences (such as coding camps), where the volume of participants is high, and teaching staff struggles to supervise all participants closely, counting on the support of tutors/teaching students assists in widening the impact of the educational process, helping others to learn and, in turn, benefit from an effective learning environment (Fronza et al., 2021). Special attention deserves the structure of role-switching where both individuals take and swap the role of mentor and mentee, using reinforcement learning to permit participants to adapt and empower the impact of mentorship on learning and engagement (Roscoe and Chi, 2007).

2.2 On Lifelong Learning Competences

Adapting Computer Science education to meet the needs of a rapidly changing technological landscape by cultivating a series of lifelong learning competencies (Area, 2018) that are technology-agnostic prepares children to adopt any new technology quickly and enable themselves and others to learn.

According to the European Commission, Member States should foster (starting at early ages and maintaining the focus on lifelong learning) the development of digital literacy and technology awareness competencies to boost suitability for employment, social inclusion, and active citizenship. Lifelong learning competencies, which can be helpful in many different contexts, are a combination of (Area, 2018): a) *Knowledge*: facts, figures, concepts, ideas, and theories that are already established and support the understanding of a particular area or subject; b) *Skills*: the ability to carry out processes and use knowledge to achieve results; and c) *Attitudes*: the disposition and mindsets to act or react to ideas, persons or situations.

The European Reference Framework identifies eight key competencies (Area, 2018) that embed problem-solving, teamwork, creativity, and intercultural skills. Digital competence involves the confident, critical, and responsible use of and engagement with digital technologies for learning, work, and social participation. Individuals should be able to use digital technologies to support their active citizenship and social inclusion, collaboration with others, and creativity toward personal, social, or commercial goals. To do that, individuals should understand how digital technologies work and how to use them to support communication, creativity, and innovation, being aware of opportunities, limitations, effects, and risks. Engagement with digital technologies and content requires a reflective, critical, curious, open-minded, and forward-looking attitude to their evolution. It also requires an ethical, safe, and responsible approach to using these tools. We take these recommendations as a beacon to define a vertical curriculum that, starting from elementary school, accompanies children in gaining skills and building confidence to pivot their roles as learners and progress from pupil to teacher as required for LbT activities.

3 EXPERIENCE REPORT

This section offers a general account of the experience of working in a robotics class, providing valuable insights into the practice of transferring knowledge and fostering technological curiosity and proficiency among young learners. As an experience report, the description is grounded in observations, interactions, and reflective practices describing a first-hand experience of the challenges and opportunities associated with facilitating a simplified robotics curriculum that nurtures critical thinking, problem-solving abilities, and collaboration skills.

3.1 Experience Setting

To exercise LbT, we chose a public Science Festival in a mid-size city (Bolzano, Italy), a free-to-attend family science day showcasing the leading edge in Science, Technology, Engineering, and Math (STEM) to encourage young people to study science in schools and universities (Canovan, 2019; DeWitt et al., 2016). Indeed, the level of family interest in science has a strong influence on future STEM participation (Dabney et al., 2013). We selected this context because Science Festivals attract a broad, non-expert, curious, and motivated to-learn population. The Science Festival showcased various talks, demonstrations, exhibitions, and interactive experiences, all centered around the theme of “Journey”. The exhibitors were mainly research centers and universities from the region.

The activity described in this work resulted from a university-school collaboration. The idea of involving high school students during the Science Festival was motivated by the documented positive effect of neer-peer mentoring on increasing the interest and engagement of high school students studying STEM disciplines (Tenenbaum et al., 2014). Moreover, social congruence (Bugaj et al., 2019) facilitates informal/empathetic communication and compensates for the lack of knowledge and expertise because teaching-students provide explanations more likely to meet the learners’ needs. Finally, the number of participants in the Science Festival (usually around 2000 people per day) made it essential to involve many instructors, which could motivate teaching-students (Fronza et al., 2023) by increasing the sense of responsibility given by the crucial role they have to play.

3.2 Participants

The 12 teaching-students (aged 15) attended a Scientific High School of Applied Sciences (four-year course). The group was gender-balanced (5F, 7M) and did not include students with special educational needs or cognitive diseases. Cultural and family backgrounds were homogeneous. An experimental class of 12 units represented a context conducive to educational innovation (Fronza et al., 2020). As described hereafter, the teaching-students completed the three stages of LbT according to the framework shown in Figure 1(Bargh and Schul, 1980).

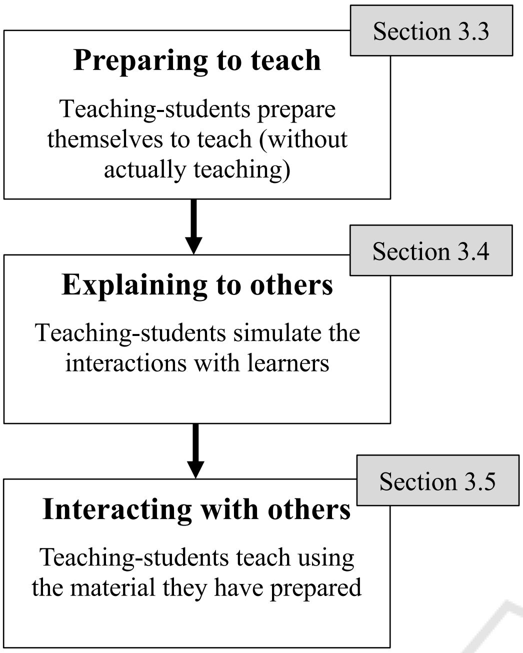

Figure 1: The three stages of LbT (Bargh and Schul, 1980): definition and mapping to the Sections of this paper that describe their implementation.

3.3 Preparing to Teach

In this phase, the teaching-students prepared themselves to teach (without actually teaching). This activity promotes learning because knowing to teach others motivates students beyond regular studying (Fiorella and Mayer, 2015).

Initially, teaching-students completed a training course of about 12 hours in which they acquired the basic skills of building LEGO-EV3 robots with two-wheel drive-based motion and implementing motion programs using color, distance, and touch sensors. Teaching-students also learned how to use the device's audio recording and playback tools and manage the display. The training started with the construction of the LEGO-EV3 robots and continued with the use of all the motors and sensors made available by the educational kit. Students worked in pairs to solve problems of increasing difficulty, in which all the programming blocks available were necessary. Each new issue required using/modifying the implementation of the previous one to promote learning (Vygotsky, 1978) and introduced the fundamental concept of the teaching material. At the end of the training phase, all the participants could implement block-based algorithms to solve educational robotics problems.

Afterward, teaching-students worked for 8 hours in groups (2 or 3 people) to create a set of flip cards as teaching material. Each group had to devise a story of fantasy or an adventure scenario to explore all the dimensions of the child (i.e., cognitive, affective, motivational, and emotional) as defined by the cognitive psychologist J. Bruner (Bruner, 1996). Each story had to be a *journey* to meet the requirements of the Science Festival. Then, students divided the journey into steps and created a card for each step, in which one needed to use all the robotics tools acquired during the training phase (motors, input through the color, touch, distance sensors, and audio).

The participants created the stories by following the "puppet metaphor" (Figure 2), which illustrates the narrative style closest to children between 6 and 10 years old (Wright, 1998). The puppet's head represents the story's introduction (i.e., *who*, *where*, *when*). Much more substantial, the puppet's body represents the story's development (i.e., *what* happens), bringing the child closer to the characters by working alongside them. Finally, the puppet's feet represent the conclusion, which briefly shows *how* the story ends: a happy ending generated by a positive event.

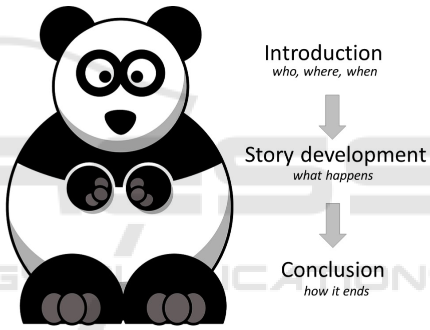

Figure 2: The "puppet metaphor" illustrates the narrative style that is closest to children between the ages of 6 and 10 (Wright, 1998). The puppet's head represents the introduction of the story, which is not very big but provides important details such as who, where, and when. The larger body of the puppet represents the story's development, which includes unexpected events and twists. Finally, the feet of the puppet, which are smaller than the body, represent the final twist and the happy ending.

Using the "puppet metaphor", the teaching-students were asked to write a story by following the following tips, which are widely used in teaching through storytelling (Wright, 1995):

- *Think about the plot*: imagine a captivating and engaging story by choosing *who*, *where*, and *when* first.
- *Imagine the main character*: define the characteristics of the main character that will interact with the child.
- *Define simple problems*: include in the story situations the main character must face with the child by programming and using the robot.

- *The implication of the story*: after a moment of maximum tension, something positive and exciting must happen (i.e., the *epilogue*), leading to a happy ending.
- *Happy ending*, with an unexpected twist.

For the preparation of the flip cards, we provided the following requirements to the students:

- One side of the card shall describe one part of the story (in a language appropriate for 6-10-year-old children), i.e., tell the child the mission that the robot has to accomplish.
- The back of the card shall provide hints to help the child with programming, i.e., show a picture of the code block, the most suitable hardware (motor or sensor), or the wizard for recording and playing sounds (Figure 3).
- Each card shall require an additional programming concept to the previous one to encourage stepwise learning.

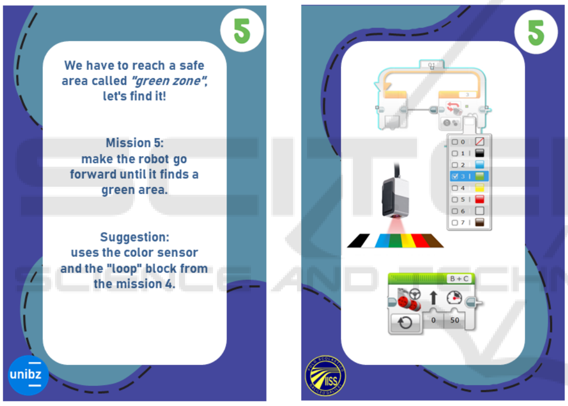

Figure 3: Example of flip cards: the proposed mission requires using the *loop* block, introduced in the previous mission by changing the output test.

This phase created five sets of flip cards, each with 12 cards. As shown in Figure 4, in each set, the first and last cards represent the preface and the happy ending; the middle ten cards allow the implementation of the fundamental components of the robot mentioned above in steps of increasing difficulty (i.e., the missions). The first mission always involves building a robot component; the others require block-based programming. Each set of flip cards has a main character, a fantasy or adventure scenario, a series of missions of increasing difficulty that the child must complete by programming the robot, and a happy ending following the ten missions.

3.4 Explaining to Others

During this phase, the teaching-students actively used the teaching material meaningfully (Fiorella and Mayer, 2015) by simulating the interaction with children. A teaching-student took the role of a learning-student to stimulate that kind of interaction with teaching-students. Other teaching-students observed the interaction, commenting on it and advising on improvement. In order to validate the process of knowledge transfer, we explored what specific concepts were understood and interpreted, paying attention to a simplified language and simulating the transition to different languages according to the children's needs.

3.5 Interacting with Others

This phase encourages students to reflect on their understanding of the material while teaching (Fiorella and Mayer, 2015). We implemented it during a Science Festival, where participants coordinated an interactive experience to let children take their first steps in robotics.

The activity took place in a room with free entrance and no reservation required. Five tables (i.e., one table per set of flip cards) surrounded by chairs were in the room. On each table (Figure 5) were a robot, a laptop, materials for unfolding the story (e.g., obstacles), and flip cards. Each table was coordinated by 2-3 teaching-students, usually those who had created the corresponding set of flip cards; however, since they knew all the set of flip cards, teaching-students changed tables throughout the day to substitute others during breaks, to change topics, or support others in managing specific needs (e.g., language and age).

Children (i.e., learning-students) could either approach the tables spontaneously or were kindly invited by the teaching-students to come. The teaching-students knew that the children could leave at each point without completing all of the missions in the flip cards or, conversely, stop and ask for more. The activity lasted 8 hours and hosted dozens of children.

3.6 Data Collection, Analysis, and Interpretation

As detailed in Table 1, in this work, we adopted multiple data collection types (Creswell and Creswell, 2017):

- ***Observations*** were semi-structured, i.e., the researchers filled in a form to annotate if they could observe behaviors or events related to LbT in each phase.

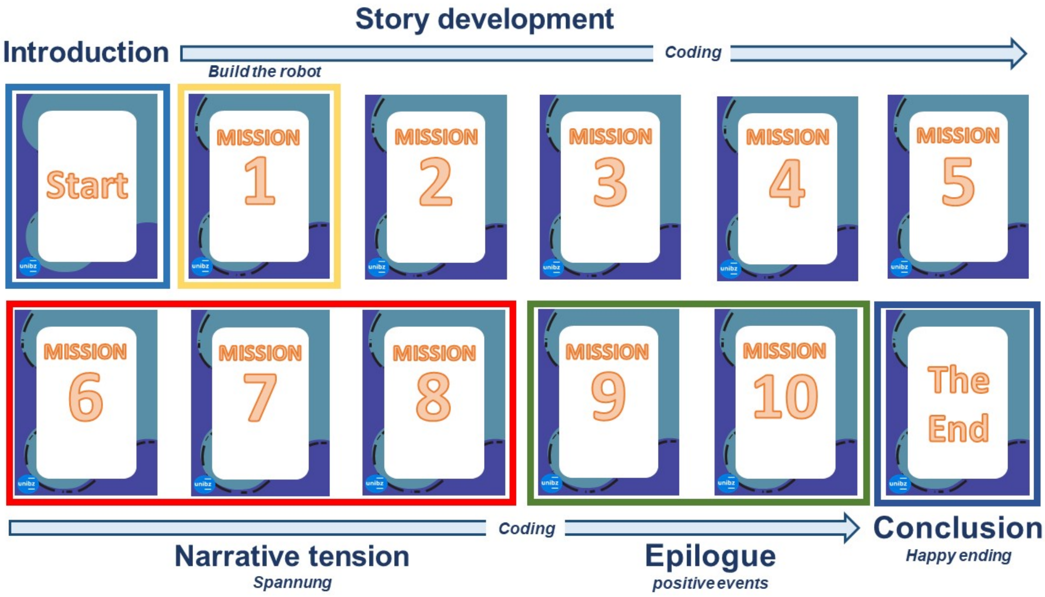

Figure 4: Structure of a set of flip cards. The first and last cards represent the preface and the happy ending; the other cards allow the story's development as missions. The first mission involves building a robot component, while the others require block-based programming. In the middle of the story (cards 6-8), there is the moment of maximum tension before the **"epilogue"** (cards 9-10), leading to the happy ending.

Figure 5: Setting of the "interacting with others" phase.

- ***Interviews*** during a *self-reflection* phase after the Science Festival: researchers engaged teaching-students in ***focus group interviews*** to elicit views and opinions complementing the observations.

Collected data were then categorized and summarized to analyze two aspects: 1) understand whether LbT benefits teaching-students in learning robotics concepts, and 2) outline the effectiveness of LbT for interactive activities targeting younger children during Science Festivals.

Table 1: Data collection strategy.

Type	Collection approach
Observations	Researchers used an agreed **observational protocol** to collect **field notes** without intervention on the target population. Students' activities were observed, focusing on how they applied their knowledge to support each other.
Interviews	Researchers conducted **focus group** interviews using an agreed-upon **protocol** during **self-reflection** after the Science Festival. Participants discussed areas of improvement, reorganized their knowledge, deduced errors, and repaired them.

4 RESULTS

This section discusses the significance of knowledge acquisition and the result of the process through which participants exercised or gained new knowledge. We structured the summary of our observations in two parts: discussing the central insight gained and additional learnings that we considered to have nurtured the learning process and paved the way for improved experiences.

4.1 Major Learnings

As major learnings, we identified and analyzed traits that allowed us to identify patterns and connections to elaborate on LbT as an instrumental strategy in the learning process that may eventually support a lasting educational outcome. We summarized the results to analyze the following two relevant aspects.

1. Understand whether LbT benefits teaching-students in learning robotics concepts.

Confirming the previous literature in the field, in our experience, LbT enhanced learning by forcing the teaching-students to retrieve previously studied information to contextualize it differently (Koh et al., 2018). In order to create the missions in the flip cards, teaching-students learned to use all the blocks of the programming language according to the specific need, thus improving their problem-solving skills. Moreover, teaching-students learned to simplify and optimize the code by witnessing children's programming mistakes. Finally, they improved their ability to communicate robotics concepts by rephrasing them several times, if needed, based on the learner's needs and difficulties.

By the end of the experience, the teaching-students had a solid grasp of the robotics concepts learned. They were also curious to extend their knowledge to solve new challenges, which often emerged from the children's questions during the Science Festival. In this regard, during the event, we could observe a decisive change in the attitude of the teaching-students compared to regular classes: feeling a responsibility to respond to children and not wanting to disappoint them, they helped each other. They worked to find a solution when they did not know an answer immediately.

2. Outline the effectiveness of LbT for interactive activities targeting younger children during Science Festivals.

The teaching-students successfully managed the activity, helped each other, and demonstrated a high level of engagement and sense of responsibility concerning the event management (for instance, organizing to take turns for lunch to avoid leaving the stand unattended). After being more conservative in their communication engagement at the beginning of the activity, they gained confidence up to being able to adapt activities and narratives to the context and language that caters to different age segments, e.g., very young children (Figure 6) and adults. Thanks to the flip cards, the teaching-students involved children at different levels: those who stayed only for two cards and then had to go and those who asked for additional missions after finishing the set of flip cards.

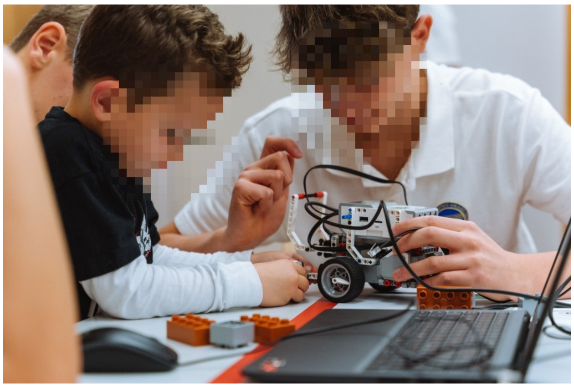

Figure 6: A teaching-student interacting with a very young child.

At the end of the Science Festival, teaching-students got back home with enthusiasm, so much so that parents wrote thank-you notes to the organizing school a few days after the event. Eight months after the project, the teaching-students remember all the activity steps, have internalized the robotics concepts, and can reproduce them naturally. They all remember the project positively, meaning it left a positive imprint on their lives. They all positively responded when asked if they would be willing to repeat the activity by bringing in other STEAM concepts.

4.2 Other Lessons Learned

In addition to the insight gained in the LbT process, we synthesize below the lessons we learned during this experience:

- Twelve hours of training were sufficient for teaching students to acquire the basic concepts of robotics and then be able to explain these concepts to children.
- Teaching-students' feedback was overall positive, but everyone reported improvement opportunities, especially in communicating simplified concepts. As a lesson learned, customized, adapted language should be explored in more detail in the learning process (e.g., when explaining complex concepts to younger children).
- The flip cards proved to be a beneficial resource to support teaching and learning. After completing the activity, we recommend investing time with the teaching-students to improve the content of the flip cards based on the experience and insight gained in the learning activity.

- Simulations before "interacting with others" are essential to lessen some tension at the beginning of the Science Festival. A smaller-scale edition of the activity with a small group of children might work even better.
- The presented activity is multidisciplinary and leaves room for exercising different competencies and adapting them to different learning preferences and interests. For instance, the conversations could mesh diverse topics like Computer Science or Civic Education.
- Our observations about the pace and natural flow of the conversation confirm that LbT exercises and puts teaching-students' soft skills into practice.

We believe that these lessons learned can be helpful to enhance the research process and help identify future development areas.

5 CONCLUSION AND FUTURE WORK

According to the observations collected in the experience presented in this work, LbT fosters a supportive and engaging learning environment and promotes trust and knowledge retention. Our insight and major takeaway is that learning-students improved their overall learning experience, and teaching-students also exercised the development of essential soft skills, such as communication, critical thinking, and knowledge transfer. These results evidence that LbT can be used as a strategy for promoting vertical alignment of the educational robotics curriculum: while interacting, different age groups can share experiences, acquire micro-language skills (i.e., the specific terminology of disciplinary and professional sectors), and find/provide the necessary support and motivation for transitioning between school years.

In addition, this work found that utilizing LbT during the Science Festival offered key advantages. It created a relatable and comfortable learning atmosphere, as the teaching-students shared similar experiences and perspectives with learning-students. This familiarity allowed for effective communication, empathy, and the building of trust, which in turn facilitated engagement and active participation. The teaching-students' previous knowledge of robotics, combined with their ability to explain concepts in simple terms, contributed to improved comprehension and enhanced knowledge transfer. Furthermore, our experience draws attention to the significance of creating an inclusive and supportive learning environment that adapts to participants' diverse needs and interests.

In our experience, the Science Festival was an excellent context for teaching-students to challenge themselves: the number of participants made clear the importance of their contribution and increased the sense of responsibility given by the crucial role they have to play. However, some tension was also present despite the simulations before the event; for this reason, a smaller-scale edition of the activity with a small group of children might be preferable.

The type of teaching material created by the teaching-students (i.e., the flip cards) has proven valuable as teaching materials for several reasons. For example, they provided a route for teaching-students to follow, avoiding uncertainty about how to start or continue; for this to happen, however, the teaching-students must create the flip cards themselves. Moreover, flip cards helped involve children at different levels: those who stayed only for two cards and those who asked for additional missions instead.

The findings of this experience report support the notion that teaching-students can effectively enhance the learning experience of their fellow students, cultivating abilities that contribute beyond technical education and construct lifelong learning. Future work may explore specific strategies teaching-students employ and additional variables contributing to their effectiveness (e.g., age gap). This experience advocates for the formal integration of LbT within educational institutions as a fundamental strategy to strengthen more traditional methods to teach robotics concepts. Moreover, the approach proposed in this work could be applied to any STEM discipline, such as chemistry, physics, biology, and electronics, which is in the authors' plans for the future. For example, we plan to customize the approach presented in this paper to introduce children to the basic principles of Generative Artificial Intelligence: high school students could learn the principles of effective prompting and build teaching material to teach younger students how to use ChatGPT.

Finally, exploring how the proposed approach could support students while learning micro-language in a foreign language through the linguistic mediation of teachers-students would be interesting.

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