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Mediating Computational Thinking Through Educational Robotics In Primary School

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par

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If I had an hour to solve a problem
I'd spend 55 minutes thinking about the problem
and 5 minutes thinking about solutions.

— Albert Einstein

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Abstract

Nowadays, computational thinking (CT) is considered a skill to be taught. While educational robotics (ER) appears promising to foster students' CT, operational CT frameworks and explicit guidance in ER are lacking. This thesis thus proposes to understand how teachers can implement ER learning activities in order to develop students' CT competences, and produced two concrete contributions:
1) The creative and computational problem solving (CCPS) model, an operational ER-CT framework that was developed to design ER-CT learning activities, and more specifically the associated intervention and assessment methods, by rendering the CT strategies of students observable.
2) The design and analysis of two complete ER learning activities to promote the full range of CT competences based on the CCPS model, including the artefacts, assessment, and intervention methods.

Both were leveraged in a multi-stage translational research process to investigate how to mediate teaching with ER to foster CT. First, 43 teachers following an ER teacher training program were probed regarding their attitude towards ER, which helped identify two distinct profiles of teachers: "pioneers" and "followers". While the former may implement ER and CT on their own, the latter need resources and guidelines to do so. The analysis highlighted the need for ER activities fostering 21st-century skills. The analysis also showed that as long as teachers can benefit from ER training and take the time to appropriate the robotic artefact (*i.e.*, the first stage of instrumentation), teachers' attitude toward ER is positive. However, to pass the second stage of instrumentation and thus organize the conditions for developing the students' CT competence with the robots, ER must be perceived as usable. For this, teachers report needing material resources and time. Since the acceptability of ER is correlated with its usability, work should focus on improving ER usability to increase its acceptability.

The next step thus entailed the design and setup of the two complete ER learning activities, which the CCPS model assessed. The intervention methods targeted the introduction of delays in students' thought process, once by preventing access to the programming interface and once by having a delay between execution and the visualization of the results of said execution. Results showed success in fostering students' CT as they went through all the phases involved in the model. Subsequently, an evaluation of teachers' acceptance of the provided learning activities, intervention and assessment methods was conducted with 334 teachers. Indeed, to orchestrate an ER learning activity for CT, the teachers need time and training to carry out the two instrumentation stages. Results showed that while teachers perceived the utility of the methods and resources provided, it was still unclear how the use of the artefacts (usability) related to students' strategies and thus CT competences. Hence, teachers need more time for the second stage of instrumentation.

More work must be done, on more extended training periods, to provide explicit guidelines that would help ensure that all teachers and not just pioneers can employ ER to foster CT competences in their classrooms. More explicit guidelines may thus further enable the CCPS model to be a tool for teachers' instrumentation of CT in ER learning activities in terms of design, intervention and assessment.

Keywords

Computational Thinking, Educational Robotics, Problem Solving, Intervention Methods, Competence, Assessment

Résumé

De nos jours, la pensée informatique (PI) est considérée comme une compétence à enseigner. Bien que la robotique éducative (RE) semble prometteuse pour la favoriser, les cadres opérationnels en PI et les directives explicites en matière de RE font défaut. Cette thèse propose donc de comprendre comment les enseignants peuvent mettre en œuvre des activités d'apprentissage de RE afin de développer les compétences en PI des élèves. Ainsi, deux contributions concrètes ont été aportées dans cette thèse:
1) Le modèle de résolution créative et computationnelle de problèmes (CCPS), un cadre opérationnel développé pour concevoir des activités d'apprentissage de RE-PI, et en particulier les méthodes d'intervention et d'évaluation associées, en rendant observables les stratégies de PI des élèves.
2) La conception et l'analyse de deux activités d'apprentissage de RE visant à promouvoir l'ensemble des compétences de PI sur la base du modèle CCPS, ainsi que les artefacts, les méthodes d'évaluation et d'intervention.

Ces contributions ont été développées dans une approche de recherche translationnelle en plusieurs étapes. D'abord, 43 enseignants suivant un programme de formation à la RE ont été interrogés sur leur attitude à l'égard de la RE, ce qui a permis d'identifier deux profils distincts d'enseignants : les "pionniers" et les "suiveurs". Si les premiers mettent déjà en œuvre RE et PI, les seconds ont besoin de ressources et de directives pour le faire. L'analyse a mis en évidence la nécessité d'activités de RE favorisant les compétences du 21ème siècle. L'analyse a également montré que tant que les enseignants peuvent bénéficier d'une formation en RE et qu'ils prennent le temps de s'approprier l'artefact robotique (*i.e.,* la 1ère étape de l'instrumentation), l'attitude des enseignants à l'égard de la RE est positive. Cependant, pour passer la 2ème étape d'instrumentation et ainsi organiser les conditions de développement de la PI des élèves avec les robots, la RE doit être perçue comme utilisable. Pour cela, les enseignants déclarent avoir besoin de ressources matérielles et de temps. L'acceptabilité de la RE étant corrélée à son utilisabilité, il a s'agit d'améliorer l'utilisabilité de la RE pour augmenter son acceptabilité.

Ainsi 2 activités d'apprentissage RE-CT ont été conçues puis évaluées selon le modèle CCPS créé. Les méthodes d'intervention visaient à introduire des délais dans le processus de réflexion des élèves, une fois en empêchant l'accès à l'interface de programmation et une fois en prévoyant un délai entre l'exécution et la visualisation des résultats. Les résultats ont montré que l'intervention a favorisé la PI des élèves au fur et à mesure qu'ils passaient par toutes les phases du modèle. Ensuite, une évaluation de l'acceptation par les enseignants des activités, des interventions et des méthodes d'évaluation fournies a été réalisée auprès de 334 enseignants. Les résultats ont montré que si les enseignants ont perçu l'utilité des méthodes et des ressources fournies, la manière dont l'utilisation des artefacts (utilisabilité) est liée aux stratégies des élèves (et donc aux compétences PI) n'est toujours pas claire. Les enseignants ont donc besoin de plus de temps pour la 2ème étape de l'instrumentation.

Des travaux supplémentaires doivent être effectués, sur des périodes de formation plus longues, pour fournir des directives explicites et garantir que tous les enseignants, et non seuls les pionniers, puissent utiliser la RE pour favoriser les compétences PI. Celles directives permettraient ainsi au modèle CCPS d'être un outil d'instrumentation dans les activités d'apprentissage de RE-PI en termes de conception, d'intervention et d'évaluation.

Mots-clés

Pensée informatique, Robotique éducative, Résolution de problèmes, Méthodes d'intervention, Compétence, Évaluation

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Chapter 1 Introduction

1.1 CT is an essential 21st-century skill that must be taught

Since Wing (2006)'s seminal article, there is a consensus that Computational Thinking (CT) is a "universally applicable attitude and skill set everyone, not just computer scientists, would be eager to learn and use" (Wing, 2006, p.33) which is as important as reading, writing, and arithmetic. Moreover, CT "resonates with so many and serves as a rallying cry for educators, education researchers, and policymakers" (Grover & Pea, 2013, p.38). It is even now considered to be part of the 21st-century skill set (Wing, 2006; Yadav et al., 2011, Romero & Vallerand, 2016; Mohaghegh & McCauley, 2016; Tabesh, 2017; Tsortanidou et al., 2019; Nouri et al., 2020) that every citizen is expected to have, despite not being part of Voogt and Roblin (2012)'s original framework[1]. It is thus both paramount and urgent to equip students with CT skills. While CT is not systematically present in all curricula (Dagienė et al., 2021), various initiatives worldwide have begun to introduce CT, not only in contexts of higher education (Barr & Stephenson, 2011) and for engineers[2], but also within compulsory K-12 curricula, often within the context of national Digital Education and more specifically Computer Science related reforms (Heintz et al., 2015; Denning & Tedre, 2021; El-Hamamsy et al., 2021b, CIIP, 2021). This is the case of multiple European countries that have begun to integrate CS and CT into their curricula (e.g., in 2012 for Estonia, in 2014 for the United Kingdom, in 2016 for France, and in March 2021 for the French part of Switzerland). Unfortunately, these reforms are presently underway despite there being a lack of consensus in the literature about what CT is and a lack of understanding on how best to foster it (Tikva & Tambouris, 2021), thus running the risk of missing their mark where equipping students with CT skills is concerned. Although there appears to be some level of convergence in Aho (2011)'s definition of CT as "the thought processes involved in formulating problems so their solutions can be represented as computational steps and algorithms", which thus poses CT as a competence rather than knowledge to be learnt, the main concern lies in fostering CT. Indeed, without adequate knowledge about how best to foster CT, teachers, who are the key to effective curricular reform, can only be ill-equipped to teach this essential skill. Indeed, while CT as a competence is not new in itself (Denning, 2009; Denning & Tedre, 2021), it is its teaching which is novel. As stated by Martin Vetterli (President of EPFL) "Computational thinking is about formulating problems in such a way that a computational method can be used to answer them. This is what most areas of research and application do today, but historically it is a basic skill that has not been taught."[2]

[1] The 21st-century skill framework was developed by Voogt and Roblin (2012) based 8 main international competence frameworks and, according to the OECD (<https://www.oecd.org/site/educeri21st/40756908.pdf>), revolves around 1) core subjects and 21st-century themes, 2) life and career skills, 3) learning and innovation skills (which can be related to existing curricula through problem-solving skills included in the mathematics curriculum and transversal skills such as collaboration, communication, learning strategies, creative thinking, reflective approach), and 4) information, media, and technology skills (known as ICT and also referred to as literacy skills and often linked to digital education).

[2] See <https://actu.epfl.ch/news/l-epfl-a-l-heure-de-la-pensee-computationnelle/>

1.2 Teachers need to be equipped to teach CT in classrooms

Agnostically of the topic, teaching relies on being able to achieve didactic transposition (Chevallard, 1989, Bosch & Gascón, 2006; Chevallard & Bosch, 2020). That is to say, if we expect teachers to teach CT, we must both 1) help teachers acquire knowledge about the topic (first level of transposition, see section 1.2.1) and 2) help them understand how best to transmit said knowledge to their students (second level of transposition, see section 1.2.2).

1.2.1 First level of didactic transposition: knowing what CT is

Achieving the first stage of didactic transposition relies on having defined what is meant by "CT", and thus "thinking", as opposed to teaching content in itself. In this regard, teaching CT is close to teaching critical thinking (another recognized 21st-century skill). Although abstraction is considered by Wing (2006) as the essence of CT, other researchers have extended the components of CT (Barr & Stephenson, 2011; Yadav et al., 2011; Grover & Pea, 2013; Bers et al., 2014) to include pattern generalization, model, simulation, algorithms, automation, problem decomposition (modularizing), parallelization, iteration, recursion, debugging. However, knowledge can be distincted between 2 types: declarative knowledge and procedural knowledge (Anderson, 1983, 1985). Indeed, there is a distinction to be made between knowing what something is and knowing how to apply it. For instance, knowing what recursion is, is declarative knowledge, whereas knowing how to proceed recursively is procedural knowledge. That is why we favour the definition of CT according to three dimensions (Brennan and Resnick, 2012; see Fig. 1-1) : i) computational perspective (*i.e.*, "the perspectives designers [or a person] form about the world around them and about themselves"), ii) computational concepts (*i.e.*, "the concepts designers engage with as they program"), and iii) computational practices (*i.e.*, "the practices designers develop as they engage with the concepts, such as debugging projects or remixing others' work").

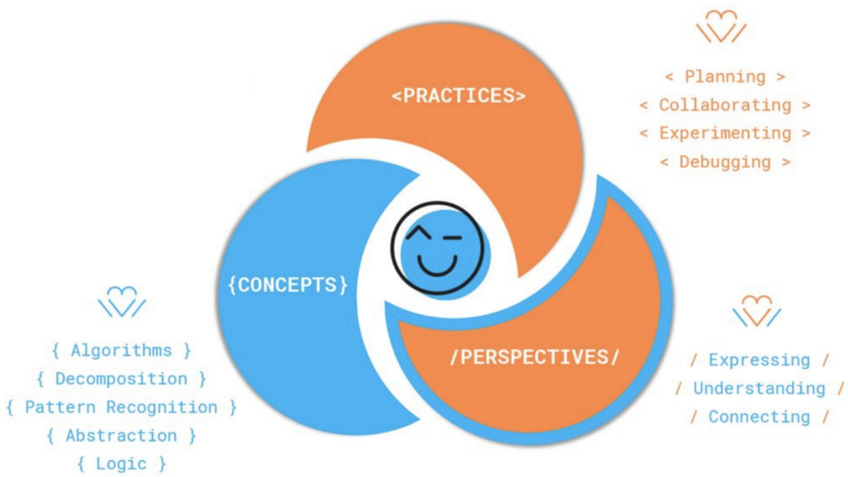

Figure 1-1 The 3 main CT dimensions according to Brennan & Resnick (2012).

(Illustration got from <http: //www.kidscodejeunesse.org/>)

Two key facets, which are highly distinct, emerge from Brennan & Resnick (2012)'s model, and must be kept in mind as it impacts how CT can be taught and assessed. On the one hand, there is an element of "situated knowledge" (Margolinas, 2014) through "computational concepts" that is related to the knowledge to be learned. Situated knowledge is often assessed through the evaluation of an outcome, which targets specific skills, cognitive abilities, and knowledge. In the case of CT, this is often knowledge which is specific to the CS field, and requires allocating dedicated time to help students familiarise with the novel tools and artefacts employed in the CT problem setting (Douady, 1987). On the other hand, there is an element of "cultural knowledge" (Margolinas, 2014) through the "computational perspectives" and "practices". Cultural knowledge is related to processes, and thus is constructed in a problem situation and requires an assessment of the learning process (and not only the output). This refers to cognitive abilities (e.g., analysis, comprehension, modeling) and specific skills (or procedural knowledge) to the practice of programming (e.g., creating a program, implementing, debugging). These dimensions must be assessed *in situ* by teachers in order to intervene adequately for each group of students as "the study of knowledge *in situ* reveals knowledge that does not correspond to any situated knowledge in the school institution" (Margolinas, 2014, translation by MC).

To conclude, since CT is a competence that must be mobilized in action and in a problem situation (Mas-ciotra & Morel, 2011; Jonnaert et al., 2004; Le Boterf, 1994), both facets, situated knowledge and cultural knowledge, should be kept in mind when creating both instructional guidelines and assessments.

1.2.2 Second level of didactic transposition: knowing how to teach CT

The key to achieve the second stage of didactic transposition lies in having identified good practices to foster the development of CT in the classroom (*i.e.*, understanding how to implement CT). That is why it is not surprising to see that most efforts are being placed nowadays on both how to foster CT and on how best to assess CT (Tikva & Tambouris, 2021). These facets are not independent and must be considered concurrently in order to achieve effective teaching, according to the principles of constructive alignment (Giang, 2020, see Fig. 1-2). Constructive alignment is based on the simultaneous consideration of four main cornerstones:

1) **The intended learning outcomes** (*i.e.*, first level of didactic transposition) that are often set by curricular standards and developmental milestones (*e.g.*, CIIP, 2021).
2) **The instruction methods** that a teacher must master in order to both design and mediate CT-related learning contexts (*i.e.*, the second level of didactic transposition).
3) **The artefacts** that are at teachers' disposal that they may use to achieve the desired learning out-come.
4) **The assessment methods** that a teacher must use to ensure that the students are achieving the desired learning outcomes.

Through this categorisation we can more clearly perceive how we can help teachers mediate CT in their classrooms.

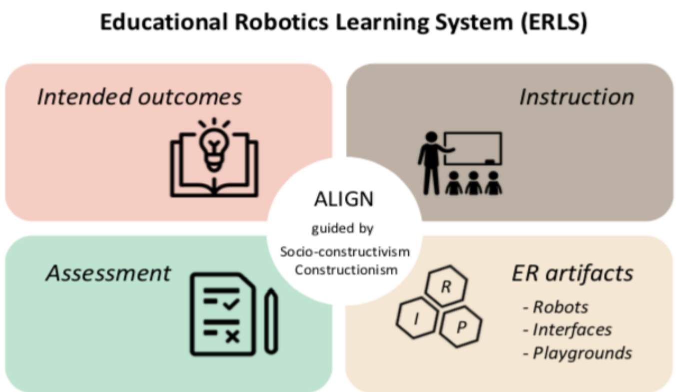

Figure 1-2 Alignment model for Educational Robotics Learning Systems (ERLS) by Giang (2020).

1.3 Equipping teachers to mediate CT

1.3.1 Through the selection of an appropriate artefact

To promote learning, teachers must propose varied learning situations to help students generalise the concepts being addressed (Algozzine & Anderson, 2007). The same holds for CT which must thus be taught through various means (*e.g*., storytelling, problem solving scenarios, metaphorical representations, game design and development etc…, Yilmaz, & Koc, 2021). That is why researchers have investigated multiple instruction modalities to practice CT skills in classroom settings (Bell et al., 2009; Tsarava et al., 2017; Brackmann et a., 2017; Bell & Vahrenhold. 2018; Saxena et al., 2020; Piedade et al., 2020; del Olmo-Munoz et al., 2020; Septiyanti et al., 2020; Bakala et al., 2021; El-Hamamsy et al., 2021a; El-Hamamsy et al., 2021b).

One key distinction which is often made is between unplugged pedagogical modalities (*i.e.*, which do not employ the use of screens, Bell et al., 2009) and plugged ones. Another distinction made is with respect to the use, or not, of robotics artefacts. In this regard, Denning and Tedre (2021, p.23) defend the presence of the machines in the teaching of CT since CT is, for these authors, « not about how to design and reason about algorithms, but about how to make machines do algorithmic tasks for people.” As teachers are often inclined towards unplugged modalities, which are close to their traditional means of teaching (Negrini 2020, El-Hamamsy et al., 2021a), we choose to focus here on the use of educational robots in problem-solving scenarios to foster CT. ER is thus another instruction modalities (a new string to their bow) that will not only help multiply the opportunities to generalize CT in classroom settings, but also has the right characteristics to support the CT (which we will explain next).

ER refers to the use of robots in education as “object[s] to think with” (Papert, 1980, p.11), which Papert considered may be appropriate for sustaining algorithmic thinking. These are generally pre-assembled robots (*e.g.*, Thymio, see Fig. 1-3a) or robotics kits (*e.g*., Lego® Mindstorms robotics kits, see Fig. 1-3b) “whose only actuators are [their] motors and display devices such as lights, sounds or a screen” (Ben-Ari and Mondada, 2017, p.8) in addition to “includ[ing] a software development environment” which can be a “version of a standard programming language (Java, Python) or [can] be simplified through a block-based language (Scratch, Thymio VPL)” (ibid., p.9).

(a) The Mobsya’s Thymio robot (b) The Lego® Mindstorms robotics kits

Figure 1-3 Two different types of educational robots (pre-assembled or in kit).

These artefacts have the particularity of being adaptable to both the unplugged and plugged modalities, and may thus satisfy a broader number of teachers (Negrini, 2020, El-Hamamsy et al., 2021a, b) by appealing to those inclined to unplugged and those inclined towards plugged in approaches. This versatility is possible because on the one hand, one may simply manipulate the robot in an unplugged way and make use of pre-programmed behaviours (*e.g.,* in the case of the Thymio robot), or, on the other hand, may program it using a visual programming interface (*i.e.*, plugged). ER also provides students with a feedback-oriented learning environment (Bers, 2007) which helps students understand abstract concepts (Touretsky, 2013; Eguchi, 2014) through the direct visualisation of the impact of their programs on the robot's actions (Bers, 2008; Bers, 2013), and thus engage in a concrete iterative design process (Hamner, Lauwers, & Bernstein, 2010). This contributes to ER also being considered a suitable medium to foster motivation and engagement in the classroom (Park & Han, 2016; Nugent et al., 2010). Indeed, in STEM (Welch, 2010; Naizer et al., 2014; Reich-Stiebert & Eyssel, 2016; Theodoropoulus et al., 2017), ER gives the opportunity to work and explore solutions to real-world problems (Miller, Nourbakhsh, & Siegwart, 2008), thus appealing to both teachers and students.

ER appears as a prominent tool, which is often associated to the development of key 21st-century skills (Romero & Dupont, 2016) such as creativity when designing and constructing robots (Komis et al., 2016; Park & Hahn, 2016; Theodoropoulus et al., 2017), collaboration (Nugent et al., 2010; Eguchi & Uribe, 2012; Ardito et al., 2014; Theodoropoulus et al., 2017), problem solving (Tsortanidou et al., 2019), as well as inquiry based learning (*i.e.*, finding the most accurate solution with "learning by doing" approach), all competences to which CT has often been associated with. It is thus not surprising to find researchers advocating that ER is beneficial for the CT competencies (Angeli & Valanides, 2020; Chalmers, 2018; Leonard et al., 2016; Bers et al., 2014; Atmatzidou & Demetriadis, 2016). Indeed, as mentioned previously CT has both a situated knowledge and a cultural knowledge component, and therefore requires being fostered in problem settings (Margolinas, 2014). This is what ER has to bring by linking both the problem solving (Park & Hahn, 2016; Theodoropoulus et al., 2017, *i.e.,* "computational perspectives and practices") and core CS concepts (Yesharim & Ben-Ari, 2017; Magnenat et al., 2014, *i.e.*, "computational concepts"). One must however understand how to design said problem solving settings in order to adequately achieve the desired learning objectives.

1.3.2 Through the investigation of which intervention methods are more conducive to the development of the desired CT learning outcomes

Despite the benefits identified in the growing body of literature on the role of ER in K–12 (Alimisis, 2013; Eguchi, 2014; Bascou & Menekse, 2016; Ioannou & Makridou, 2018, Papadakis et al., 2021), Anwar et al. (2019) report that there is "still a need to connect the theoretical basis of robotics usage with its implementation" (p.20). Indeed, the presence of a computer or a robot in a classroom does not necessarily mean that students will achieve the desired learning outcomes as robots are a "mere vehicle" of knowledge (Clark, 1983) that cannot alone influence student knowledge. Reflection on their orchestration (Dillenbourg, 2013), and therefore on their use in classroom-based learning environments, may be lacking. Indeed, as stated by Clark (1983, p.445) "media are mere vehicles that deliver instruction but do not influence student achievement any more than the truck that delivers our groceries causes changes in our nutrition. Basically, the choice of the vehicle might influence the cost or extent of distributing instruction, but only the content of the vehicle can influence achievement".

The consequence is a lack of specific models in the state of the art to understand how to foster CT in ER contexts. Specifically, while a few studies report on how to implement ER activities for CT development in classrooms, with three meta-analyses having addressed the topic (Hsu, Chang, & Hung, 2018; Jung & Won, 2018; Shute et al., 2017), they referenced only four studies between 2006 and 2018 that clarified the CT implementation through ER in K-5 education (particularly for grades 3 and 4, *i.e.*, for students between 8 and 10 years old). Another study (Ioannou & Makridou, 2018) has shown that there are currently only nine empirical investigations at the intersection of ER and CT in K-12. Therefore, among the recommendations for researchers presented, Ioannou & Makridou (2018) stated that it is essential to "work on a practical framework for the development of CT through robotics". Researchers must however not forget to address the issue raised by Lye & Koh (2014), *i.e.*, the lack of specific intervention approaches to foster both the “computational practices” and “computational perspective” dimensions, and thus consider the full range of competencies involved in CT when investigating intervention methods.

The consequence of said lack of ER-CT frameworks is a lack of "explicit teacher guidance on how to organize a well-guided ER activity to promote students' CT skills" (Atmatzidou & Demetriadis, 2016, p. 662; Ioannou & Makridou, 2018), and in particular the processes involved in CT (cultural knowledge) which require immediate action. Indeed, as Bruner (1983) highlighted in his theory on tutorial interaction, the relationship between teachers and students is essential in a new learning process. Teachers play a key role in mediating knowledge for students (Bruner, 1983) and are able to scaffold the task for students and provide temporary support and gradually fade it out in order to help the learner progressively learn to carry it out alone. The same applies in ER and CT classroom-based contexts, which is why it is essential not only to train teachers to identify the relevant features of educational robots (El-Hamamsy et al., 2021) and help them with their first instrumentation, but also to provide them with an understanding of how to use ER to support and mediate learning for CT. However, one prerequisite to be able to mediate ER-CT learning activities lies in having an adequate tool to assess learning, in alignment with the desired learning outcomes (Giang, 2020).

1.3.3 Through the development of an assessment method which is adapted to the intended learning outcomes in an educational robotics learning setting

As mentioned in section 1.2.1, CT is a competence which encompasses both the processes (cultural knowledge) and the result of the student's activity (situated knowledge). In accordance with this duality, and when considering the need to ensure that ER-CT learning activities foster the full range of competencies involved in CT (Lye & Koh, 2014), it is all the more important that CT assessment modalities include both the "output of thought" and the "thought process" (Zhong, 2016). However, it is precisely these "thought processes" (Aho, 2012; Wing, 2006) for which it is difficult to elicit evidence (or traces) and thus to assess directly. Unfortunately, being able to identify said traces is necessary so that teachers may observe the students’ cognitive processes and subsequently engage with them to develop CT. This difficulty is reflected in the literature on CT assessment. While there is a growing body of research on this topic, studies generally focus on the students' CT performance (*i.e.,* result of the mental activity, Zapata-Cáceres et al., 2020) and thus attribute a score to the result of students’ performance. Few researchers investigate the students’ strategies, or CT processes (evidence of mental activity, Merkouris & Chorianopoulos, 2019) and actually identify the processes mobilized and developed by the students throughout the creative and computational problem-solving activity. Even less studies take into account both facets, although they should not be dissociated (Coulet, 2011). This is because success in solving a computational problem (output) does not ensure that one has developed the desired CT competence (thought process) and failure to achieve the desired output does not mean that one has not employed adequate processes to attempt to resolve the task.

To illustrate, a student may have achieved the desired learning outcome by employing an alternative strategy which exploits weaknesses in the artefacts available in the problem-solving setting, thus circumventing learning objectives. This relates to how an instrument mediates actions between a subject and an object (*i.e.,* instrumental genesis, Rabardel, 1995; Béguin & Rabardel, 2000), and thus to the selection of artefacts which, in accordance with the principles of constructive alignment (Giang, 2020), can play a significant role in problem-solving strategies and thus in developing and assessing CT. Indeed, students appropriate the available objects (robot, playground, pedagogical constraints, *etc*.) and use them (instrumentation) in the service of the goal to be achieved (often the completion, or even the success, of the task) although rarely to achieve the underlying learning objectives of the task (which also include transversal competencies and cognitive processes). Consequently, the artefactual affordances provided (Kalmpourtzis & Romero, 2020) should be identified a priori by teachers so they may understand how the use of the artefacts (instrumentation) relates to the underlying strategy employed. This helps teachers not only in understanding how to mediate learning around the artefacts, and orchestrate learning activities that foster CT skills, but also in planning adequately pedagogical intervention. Indeed, teachers must be able to identify and assess conjointly the cognitive processes at play (cultural knowledge) with respect to the use of the artefacts (here, educational robots), and their impact on the outcome (situated knowledge) in order to design and orchestrate ER-CT learning activities.

1.3.4 Through the evaluation of the adequacy of the artefacts, intervention and assessment methods for teachers in the field

With the ultimate objective of facilitating the design and orchestration process of ER learning activities that foster CT skills for and by teachers, teachers must appropriate educational robots into their practices. Similarly to didactic transposition (Chevallard, 1989), the instrumentation of technology happens in two stages (Trouche, 2003). Teachers must first learn about the artefacts and be familiar with the desired learning objectives to alleviate any reticence towards to be willing to accept and integrate them into their practices. Teachers must then understand how to interpret students' strategies and outcomes conjointly in order to design and orchestrate their teaching accordingly.

The first stage of instrumentation of ER for CT by teachers. As mentioned previously, teaching CT is a novelty (particularly in compulsory education), and while ER is not novel in itself, it is only recently that ER has begun to be introduced into formal education (CIIP 2021, El-Hamamsy et al., 2021a, b). These novelties may thus lead to reticencies from teachers who are unfamiliar with CT and ER, despite it being critical to ensure that all stakeholders perceive robot-aided education favorably and that this meets their needs in order to successfully introduce it as a new technology to support educational practices (Lee et al., 2008). Indeed Negrini (2020) and Kradolfer et al. (2014) have suggested that teachers' attitudes towards ER may be negative if they perceive ER to be costly financially, with respect to training time, or time to design robotics activities. Teachers may also fear not having the competences to master ER (from both the technological perspective and in terms of classroom management) or that the ER potential for their classes is irrelevant (*e.g.*, that the students are too young, or that there are too many to orchestrate a lecture). Given that a teacher's attitude is a strong predictor of the use of technology in classrooms (Kennedy, Lemaignan & Belpaeme, 2016; Lee, et al., 2008), and that they play a crucial role in leading the implementation of ER, particularly in STEM education (Papadakis et al., 2021), it is critical to train teachers and ensure that they perceive the utility of ER and CT, that they are able to make use of it, and that they are willing to integrate it into their practice (Tricot, 2003). Moreover, different studies have shown that teachers' attitude towards ER improves following an introduction to educational robots (Castro et al., 2018) and that this is not dependent on age or gender (Kim & Lee, 2015; Reich-Stiebert & Eyssel, 2016; Negrini, 2020; El-Hamamsy et al., 2021b).

The second stage of instrumentation of ER for CT by teachers is contingent on giving teachers adequate intervention and assessment methods which they may use in their practices. As stated in sections 1.3.2 and 1.3.3, these are presently lacking in the ER-CT literature, with little research providing explicit guidelines on how to foster and evaluate all facets of CT in ER learning activities, that is to say both processes (cultural knowledge) and outcomes (situated knowledge). Contributions must be made along these axes in order to help teachers take a step forward and introduce ER-CT into their practices.

1.4 Problem setting and research questions

The literature review presented in this chapter and summarized in Figure 1-4 has helped show that CT is an important topic, which, while not novel in itself, is novel to teach. In order to teach any topic, a teacher must be able to do what is called didactic transposition (Chevallard, 1989, Bosch & Gascón, 2006; Chevallard & Bosch, 2020) which here relies on 1) understanding what CT is and identifying what it means to teach CT and 2) understanding how to teach CT. While CT has had multiple definitions in the past, including a decomposition into concepts, perspectives and practices (Brennan & Resnick, 2012) at its core is the distinction between situated knowledge (related in this case to computational concepts) and cultural knowledge (related to computational perspectives and practices). With this conception of CT in mind, we can investigate the design and mediation of knowledge by teachers (Brunner, 1983) in the context of learning activities that foster the full range of CT competences. This however is dependent on the alignment (Giang, 2020) between:

- The learning objectives, in our case the three components of CT posed by Brennan & Resnick (2012) as described in section 1.2.1 which we consider in the context of K-5 (lack of studies, see Fig. 1-4);

- The artefacts, in our case educational robots which appear to be a promising tool to foster CT (see section 1.3.1), and more specifically the Thymio robot, a gender-neutral mobile robot with a visual programming environment, that is considered to be “generic” (Ben-Ari & Mondada, 2017, p.11);

- The instruction modalities, which the literature in section 1.3.2 has shown to be lacking in the case of ER and CT frameworks, thus contributing to a lack of explicit guidelines 1) with respect to the development of computational perspectives and practices (Lye & Koh, 2014) and 2) for teachers so that they may mediate learning (Atmatzidou & Demetriadis, 2016, p. 662; Ioannou & Makridou, 2018);

- The assessment methods, which are critical to teachers’ understanding of where the students stand, in terms of processes and outcomes, in relation to the learning objectives and artefacts in the environment, and thus ability to mediate the learning process. Unfortunately, few CT assessment frameworks consider cultural knowledge (processes), and even less consider it conjointly with situated knowledge (outcomes), despite the importance of simultaneously assessing them (Coulet, 2011), as shown in section 1.3.3.

Furthermore, it is not sufficient to provide such a framework to teachers to ensure they will appropriate it and introduce it into their practice. As such, it is essential to ensure that teachers go through the two stages of instrumentation (Trouche, 2003) and 1) acquire knowledge of the tools at play (educational robots) and are willing to integrate into their practices, which is contingent on its utility, usability and acceptability (Tricot, 2003), and 2) feel capable of mediating learning in ER-CT contexts.

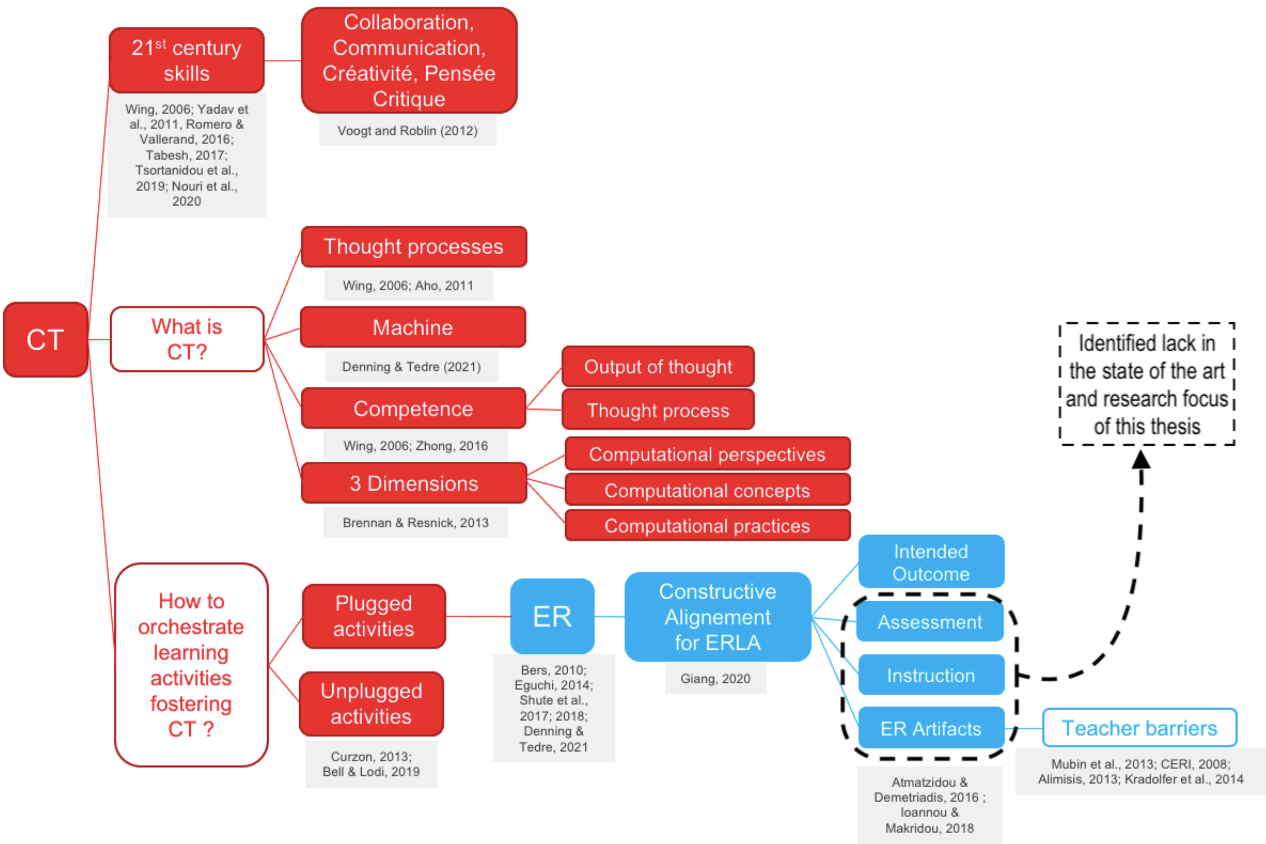

Figure 1-4 Summary of the state of the art and identified lack addressed in this thesis.

The objective of the thesis is to address the following research question in the specific case of 8-9-year-old students: **How can teachers implement educational robotics (ER) learning activities to develop the students' computational thinking (CT)?**

To answer this question, provided the afore-discussed gaps which must be addressed in order to help teachers mediate ER learning activities which foster CT skills in their classrooms, we consider the following subquestions (Sub-RQ#1 to Sub-RQ#4):

1) How do teachers perceive the use of a robot in their classroom?

2) How can the emergence of CT during ER learning activities be modeled?

3) What intervention methods can foster students' CT during ER activities?

4) How do teachers perceive the ER-CT model and the ER learning activities fostering CT?

As an article-based thesis, the following chapters aim to describe the main research outline (chapter 2), to summarise each published study (chapter 3) and subsequently to discuss these four research subquestions (chapter 4) in order to finally conclude by answering our main research question and opening up the limits of our research and future work (chapter 5). The four articles of this thesis can be found in the appendices.

Chapter 2 Research outline

To address the research sub-questions (Sub-RQ#1 to Sub-RQ#4) to answer the main research question (QR) of this thesis, different studies (3 published and 1 submitted and accepted with revisions) were conducted. In this section, we present the method from a global point of view that has allowed us to articulate all of these studies.

2.1 From a translational research approach

As presented in chapter 1, the goal of this thesis is to **understand how primary teachers can use educational robots to foster computational thinking (CT) among 8-9-year-old students (K3-6).** To achieve this goal, we used a translational research approach that aims to "bridge the gap between research and practice" (Mitchell, 2016, p.4) *i.e.*, to translate or convert concepts to classroom practice (Leask, 2013). Indeed, while CT has entered the educational sphere since 2006, its implementation in the classroom is not widespread even though the state of the art points to both the interest in developing students' CT competences and this through ER (see Chapter 1 and Fig. 1-4). According to Mitchell (2016), "the challenge beyond doing research is to make it easier for practitioners and policy makers to find, understand and apply research" (p.4.).

In order to aim for generalisation or scaling up, it therefore seems relevant to use this translational research approach as it allows for different levels of understanding by different stakeholders. This research approach is increasingly used in the health sector, but also in education (e.g., see the MESH collaborative initiative[3]) to promote the dissemination of work and thus enable society to benefit from it quickly. With this in mind, we have chosen to communicate in journals, conference and training courses the results of our work throughout this thesis (hence this thesis based on articles). As part of this translational research and to achieve our research goal, we went back and forth between the state of the art and classroom practice.

In this regards, two distinct but complementary approaches were mobilized: on the one hand, from a bottom-up perspective, we had an inductive approach to draw principles from the practice of teachers and students; on the other hand, from a top-down perspective, we had a deductive research approach to explain the phenomenon of CT by testing our assumptions (see Fig. 2.1.).

[3] See <www.meshguides.org>

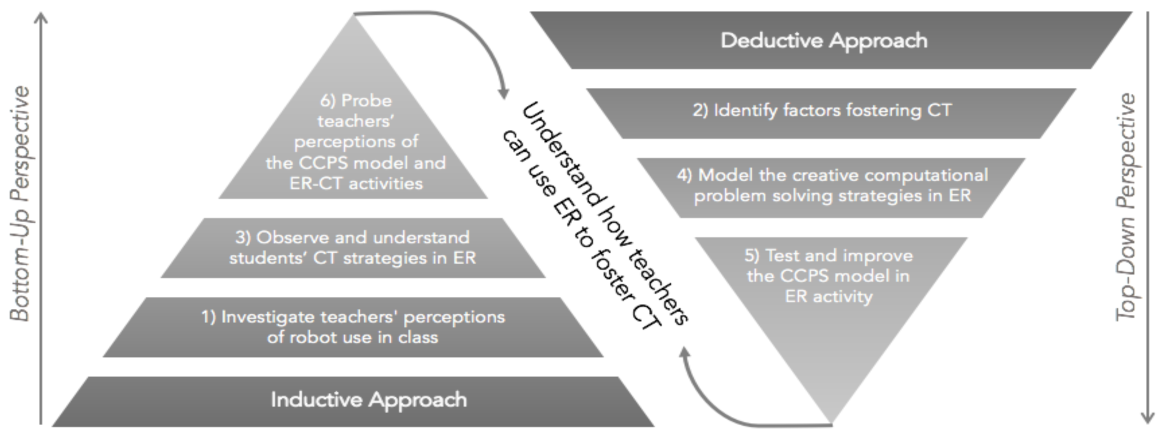

Figure 2-1 Two complementary perspectives to reach the goal of this thesis with back and forth between induction and deduction approaches.

Indeed, to **understand how primary teachers can use ER to foster CT**, we need to know both the reality of the field and what has already been provided by the state of the art. The following steps explain deeperly the Figure 2-1:

1) As a result, and as CT was not known in our research sample, in study 1 (Chevalier et al., 2016), we used a survey approach to explore and understand teachers' habits in ER in terms of utility, usability, acceptability (Tricot at al., 2003). From this survey, we were able then to identify best ER practices and motivational factors for teachers to implement ER activities in the classroom.

2) Based on such factors and practices from our bottom-up perspective, we could design ER activities also in line with what was noted in the state of the art (top-down perspective).

3) Subsequently, we could observe and understand the students' CT strategies in such an ER design.

4) This led us to model in study 2 (Chevalier & Giang et al. 2020) the Creative Computational Problem Solving (CCPS) cycle in ER that guides us in both the development of activities and the analysis/evaluation of learning processes.

5) We then tested this model with students in an ER experimentation in both study 2 (Chevalier & Giang et al., 2020) and study 3 (Chevalier et al. 2021).

6) Afterwards, in study 4 (Chevalier & El-Hamamsy et al., 2021) we probed the teachers' perception of this model and the intervention methods used to foster CT in the ER activity. Finally, we could improve and test new intervention methods that could foster CT in ER activities.

As a result, on the one hand, through our approach, we sought to intervene by designing and evaluating the effects of different pedagogical practices in CT-ER using rigorous methods. On the other hand, through our back and forth, we took into account the fact that our designs and guidelines could be translated, interpreted and adapted during their implementation by the actors in the field. This is what translational research is all about.

2.2 Into four phases and different samples

Through these studies, the sample studied is of different natures according to our needs of investigation or experimentation.

On the one hand, we had a sample of teachers that were of two kinds: future teachers (novices) and in-service teachers (experts). Nevertheless, insofar as the themes of ER and CT are new to the population of teachers from the canton Vaud (Switzerland), the in-service teachers could be considered as novices. In this case, the precision is made in the studies. This sample was working in cycle 2 or grade 3-6 of the compulsory school in the canton Vaud (Switzerland), *i.e.*, with students aged 8 to 12 years.

On the other hand, we had a sample of students aged 8-10 years in compulsory school (grade 3-4). Our experiments related to learning effects therefore focus on this specific age group.

To better understand our methodology in this thesis work, we summarize the operationalization of our research approach in Table 1, in which four phases are directly linked to the four articles of this thesis. The hierarchy (link with the relevant research phase) and references of the articles are shown in Figure 2-2.

Table 1 Summary of the different research phases with the types of data to be collected, their sources, the collection and analysis methods.

Number and name of the phase	**Data requirements**	**Sources of information**	**Data collection methods**	**Analysis techniques**
Phase 1: Teachers' initial perceptions of ER	Teachers' representations of the use of robots in the classroom in terms of their usefulness, usability and acceptability	Expert teachers (those with a proven practice in ER) Novices teachers in ER (those with no practice in ER but who are interested in it through continuing education in ER)	Questionnaire	Quantitative analysis
Phase 2: Modeling a learning situation in ER that promotes CT	The CT levers The principles underpinning ER system (ERS) Students' strategies during an ER mission that promotes CT	State of the art Expert teachers and researchers in education Students in K3 and K4 (average age 9 years)	Preliminary research with focus group Video observations in situ observations to capture the interactions of the students with each other as well as with the different ER artefacts	Qualitative analysis
Phase 3: Improving the ER system to promote CT	Student Scores (pre- and post-test) in CT Students' strategies during an ER mission according to the model developed in Phase 2	Students in K3 and K4 (average age 9 years)	MCQ (pre-post) Video Observations	Quantitative and qualitative analysis
Phase 4: Teachers' perspective on fostering CT through ER	Teachers' perception of the CT model developed in Phase 2, of the ER activity, of the intervention methods	In-service and pre-service teachers	Questionnaire Focus groups	Quantitative analysis

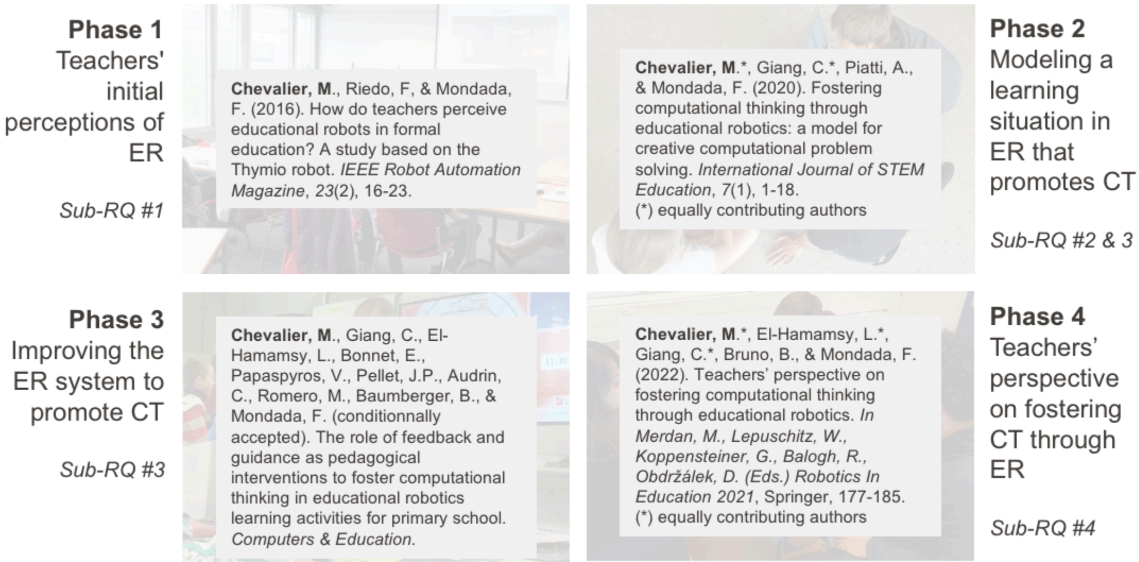

Figure 2-2 The four papers and their reference, constituting the outputs of each of the four phases.

Chapter 3 Summary of Results

This chapter presents the main results of each of the four papers that constitute the current thesis work. Each article can be considered as the output of each of the four phases of the current thesis. To better understand the articulation, each of the following sections presents the motivation, the main results, and the link with the rest of the thesis of each paper. Answering several sub-questions related to each paper will allow us to answer the main research question of this thesis.

3.1 Phase 1: Teachers' initial perceptions of ER

With permission of all co-authors and giving the pre-print version, this section is a synthesis of the following article:

Chevalier, M., Riedo, F., & Mondada, F. (2016). How do teachers perceive educational robots in formal education? A study based on the Thymio robot. *IEEE Robot Automation Magazine*, 23(2), 16-23.

As the first author of this publication, my contribution to this work involved: conceptualization, methodology, formal analysis, investigation, data curation, visualization and writing - original draft preparation.

3.1.1 Motivation

Since the late 1970s, Papert (1980) has extolled the virtues of robots, and yet, as promising as they are, robots are not systematically used in classrooms. State of the art allowed us to suggest some answers to this absence: to use robots in the classroom, teachers need hardware (Mubin et al., 2013) as well as knowledge about the proposed functionalities (Lee et al., 2008); furthermore, this use depends on flexibility and dynamism in schools (CERI, 2008), evidence about educational benefits (Alimisis, 2013) as well as on institutional injunctions (Kradolfer et al., 2014). Indeed, the September 2016 injunction in France[4] to learn programming from the first cycle of learning, for instance, resulted in an increase in the use of robots in the classrooms (virtual or physical). Similarly, the project of introduction of computer science in schools in canton Vaud, Switzerland, resulted in the introduction of robots in the official school manuals[5].

While these injunctions have strongly driven the introduction of ER into classrooms, it is essential to also consider the teachers' perspective to get a better understanding of the mechanisms underlying the introduction of robotics in schools. The first research work performed in the framework of this thesis therefore presents a survey with compulsory school teachers interested in ER (actual or desired practice). The findings of this research will allow us to partially answer our main research question by addressing the first following sub-question: **How do teachers perceive the use of robots in class?**

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[4] See <https://eduscol.education.fr/technocol/actualites/archives/2015/les-nouveaux-programmes-2016>
[5] See <https://www.plandetudes.ch/web/guest/en/cg>

3.1.2 Main results

Our survey was conducted as part of the National Center for Competence in Research (NCCR) “Robotics”[6] between 2013 and 2014. Following the training of 214 in-service teachers in the French-speaking part of Switzerland (teaching pupils aged 4 to 15), we could probe 43 of them (*i.e.,* 23.9% of the population). This population had a positive bias towards robotics, as they had enrolled in the training voluntarily. Therefore, we did not consider our results as representative of the general teacher population but rather as an indicator of how trained teachers perceive the use of the Thymio robot in their classrooms. To answer our research question (why do teachers use/would use Thymio in class?), we articulated the following concepts: usefulness, usability, acceptability (Tricot et al., 2003) and in particular, we used the intrinsic/extrinsic motivational dimensions (Deci & Ryan, 1985; Vallerand, 2000) to describe acceptability.

Our results show that the teachers surveyed (whether or not they have already used the robot) perceive a strong pedagogical usefulness of the robot. They particularly perceive the robot as helpful in achieving math and science learning goals and address interdisciplinary skills such as creative thinking, reflective thinking, and collaboration (included in the 21st-century skills framework). Nevertheless, the usability of the robot is not perceived in the same way: the teachers who have already used Thymio in their class believe that it is not necessary to have computer skills, whereas, for the others who did not test the robot with their students, this seems to be a perceived impediment. Also, we note a correlation between perceived usability and acceptability. Therefore, by improving the usability of the robot (through in-service training and adapted learning activities), teachers' acceptability would improve.

In line with the state of the art, we could observe that the fact that robots are not explicitly mentioned in the curricula (at the time of this paper, in the French-speaking part of Switzerland) and the lack of time needed to appropriate such artefacts lead some teachers to think that the Thymio robot is not directly relevant for their class.

We finally noted two trends: on the one hand, a sub-group of teachers could be characterized as "pioneers" because of their self-determined solid motivation (Deci & Ryan, 1985). In contrast, the other sub-group of teachers could be characterized as "followers" because their motivation depends on external factors and pressures. Note that these last teachers are also motivated, but this motivation is not characterized in the same way. Followers may be thus sensitive to guidelines.

3.1.3 Links with other research and a partial answer to the RQ

With this first paper, we can attempt to answer the first part of our main research question. Indeed, we can address the following sub-questions stated at the end of chapter 1. We summarize the answers in Table 4.1.

According to teachers (both pioneers and followers), an ER activity should allow the development of STEM and transversal skills. Such “learning and literacy” skills have often also been referred to as 21st-century skills. As CT has been linked to 21st-century skills (see chapter 1), and despite this is not in the terminology used by the teachers, it seems that teachers would consider robots as an appropriate tool to foster the CT competence of their students.

[6] See <http://www.nccr-robotics.ch/>

Table 2 Summary of the different answers to first subquestions (from paper #1).

Sub-question	Results from phase 1 published in paper #1	Guidelines for designing ER activity

How do teachers perceive the use of robots in class ?	Based on the UUA approach, it seems that:
	- Usefulness: ER is a relevant medium to promote STEM and transversal skills such as:
	  - reflective processes (93%)
	  - collaboration (90%)
	  - communication, learning strategies, and creative thinking (70%)
	- Usability depends on the experience of manipulating robots
	- Acceptability is correlated to usability.
	
	Two different profiles emerged:
	  - "Pioneers" are teachers with self-determined solid motivation,
	  - "Followers" are teachers with a motivation depending on external factors.
		By making the robot usable, its acceptance is assured. The ER activity must, therefore, allow students or teachers to appropriate the robot by manipulating it first.
		
		For followers, the ER activity must be linked with current explicit curriculum objectives.
		
		The ER activity must allow students to develop 21st-century skills such as "learning skills" and "literacy skills".

Based on this first outcome, we designed ER material in line with 21st-century skills, mainly aiming to foster CT. In order to assess this learning material, an instrument was needed. We thus built a model that we present in the next section.

3.2 Phase 2: Modeling a learning situation in ER that promotes CT

With permission of all co-authors and giving the pre-print version, this section is a synthesis of the following article:

> **Chevalier, M.***, Giang, C.*, Piatti, A., & Mondada, F. (2020). Fostering computational thinking through educational robotics: a model for creative computational problem solving. *International Journal of STEM Education*, 7:41.
>
> **both first authors*

As one of the two equally contributing main authors of this paper, my contribution to this work involved: conceptualization, methodology, formal analysis, investigation, data curation, visualization and writing - original draft preparation.

3.2.1 Motivation

Having investigated teachers' perceptions of ER use in the classroom, it is now appropriate to focus on the phenomenon of CT and, in particular, its emergence from ER learning activities. In most ER activities, students have to solve open-ended problems collaborating in a group of peers. In many cases, teachers let them work without any particular constraints (Buss & Gamboa, 2017; Sadik et al., 2017) in an unguided hands-off approach to teaching. In such an approach, students can rely on a trial-and-error strategy. Nevertheless, such strategies may not be considered optimal since they may "support task completion but not skills development" (Antle, 2013). This point needs, therefore, to be addressed at the design level so that the trial-and-error strategy when programming a robot always allows for systematic iteration and not blind trial-and-error till a solution appears.

Moreover, we learned from the previous phase that while the "pioneer teachers" have all the skills to self-direct and thus would find out about (or even create) the correct use of robots to foster students' CT, a large part of the teachers is considered as "follower" and needs external support to engage ER practice in the classroom. Guidelines and ready-to-teach materials can be considered as external factors or recommendations. However, recommendations about how to foster CT through ER are precisely lacking (Atmatzidou & Demetriadis, 2016; Ioannou & Makridou, 2018). During this phase 2, we aim at creating such recommendations. In this regard, two elements are needed:

- an ER learning activity aiming at fostering CT competence, whose design would be based on transversal skills (such as collaboration, communication) as stated in phase 1.
- An instrument for planning and assessing that the ER learning activity precisely fosters CT competences.

While the first element could be deduced from the state of the art and some field experience, the second is a more complex issue: although previous works have proposed different models and frameworks to describe the underlying concepts of CT (Shute et al., 2017; Romero et al, 2017), very few have discussed how ER activities should be implemented in classrooms to foster CT skill development effectively.

In this second phase, we had to design both the ER activity and the model for planning and evaluating that activity. We then performed a study with primary school students to validate the activity and the model. Phase 2 targets the following sub-questions to eventually answer another part of our main research question: **How can the emergence of CT during ER learning activities be modeled? What intervention methods can foster students' CT during ER activities?** We synthesize the answers in Table 4.2.

3.2.2 Main results

Design of the activity and the model. Designing an ER activity promoting transversal skills (such as "communication" and "collaboration") and CT was based on the following principles: groups of 2-3 students, with *a priori* non-conflictual relationships, a common goal to achieve (Patel et al., 2012), whose tasks to achieve it are defined according to their ZPD[7] (Vygotsky, 1964), a criterion for the success of the task, and an engaging context such as the robot and the authentic situation referred to (Durning & Artino, 2011). Based on these principles, we sought to create a positive interdependence (Harvey et al., 2000) of the group members (see Fig. 3-1) that foster, therefore, communication and collaboration during the ER project, and moreover, CT competences.

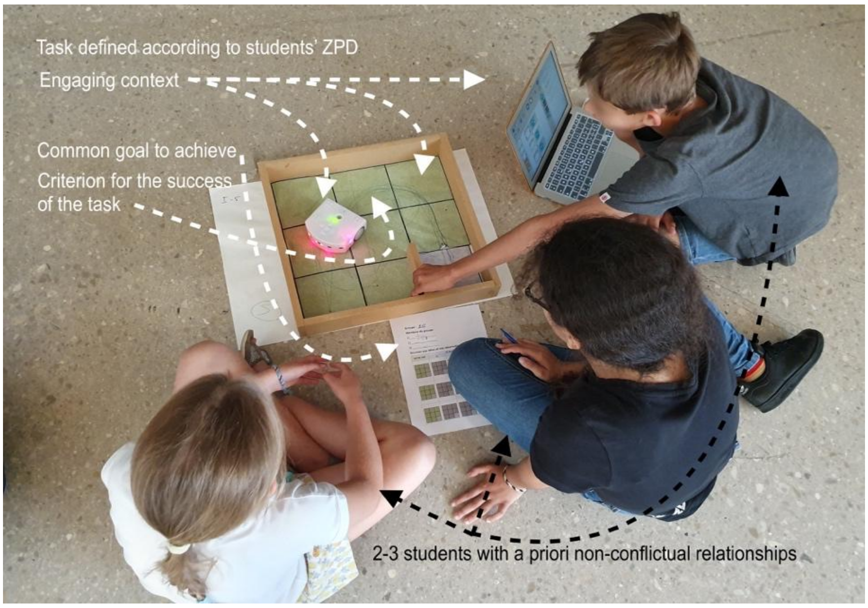

Figure 3-1 Principles taken into account for designing an ER activity promoting transversal skills such as "communication" and "collaboration".

To address the issue of a potential non-optimal Trial-and-error strategy (Antle, 2013), we designed the ER learning activity with a specific educational intervention: we block access to the robot's programming for a given time. This was inspired by previous work on inquiry-based learning (Bumbacher et al., 2018; Dillenbourg, 2013; Perez et al., 2017). The effect of this constraint is explained in the following section.

To aim at fostering CT competence, we designed a task (the lawnmower Thymio, see Fig. 3-1) which implies students to "formulate problems so their solutions can be represented as computational steps and algorithms" (Aho, 2011). In particular, students had to program a lawnmower behaviour, which autonomously drives the robot out of its garage and, in the best case, makes it pass over all lawn squares (see the 8 green squares on Fig. 3-2) while avoiding any collision with the fence. The instruction, associated with a Thymio equipped with a pen drawing on the ground, was worded as follows: *"Thymio must mow the lawn autonomously. The mission is successful if, in each of the 8 squares, there is a pen trace"*.

[7] According to Vygotsky, the Zone of Proximal Development (ZPD) is what the child can do with the help of others (a parent, a teacher, a peer) and cannot do alone.

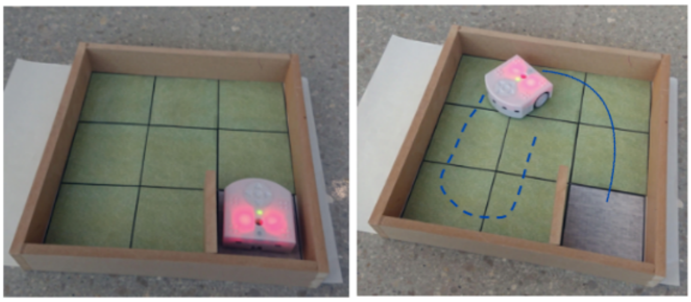

Figure 3-2 Illustration of the lawnmower task.
On the left, the Thymio robot is in the garage. On the right, the Thymio robot has already cut 3 squares of grass (see the full blue line) and, to achieve the mission, it will have to cut the other 5 green squares (see the dashed blue line).

Before this task, the students had 12 lessons of one hour each on the Thymio robot. This time is not negligible as it allows students to acquire and consolidate their knowledge of the "system" i.e., according to Romero et al. (2017), the "formal system" (COMP.3) and the "physical system" (COMP.4). In this model, these two CT components thus refer to the discipline of computer science (CS). It is during learning activities specifically aimed at these two components that the teacher makes CS concepts explicit (*e.g.,* the concepts of event, condition, state, or the concepts of sensors, actuators).

Although this task seems to involve CT competences in solving it, there was still a need to design an instrument to plan the task, to plan the possible pedagogical interventions, and to assess the development of the CT phenomenon in this task. In this respect, we were two evaluators who watched separate videos of students in class solving problems in ER (as we are interested in this task in particular) and our aim was to identify the invariants in the students' activity: we had to identify the visual and verbal observables that were recurrent in these videos (see left part of Fig. 3-3). We then agreed on the relevant observables *i.e.,* we discussed the meaning of the observed behaviours in order to suggest the subjacent intentions that allow us to approach the cognitive state of the students (see middle part of Fig. 3-3). This led us to define 6 common phases (see right part of Fig. 3-3).

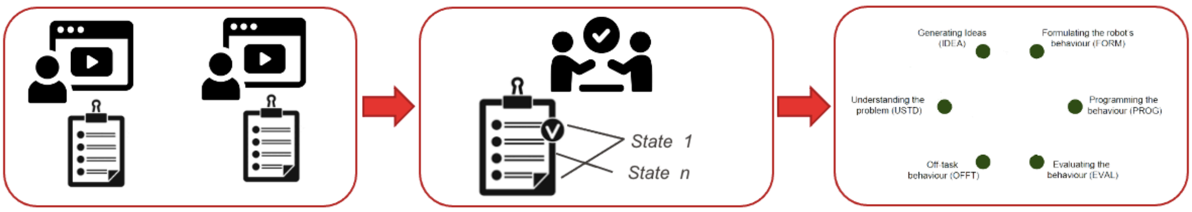

Figure 3-3 Method to design the CCPS model.

As a result, we developed the Creative Computational Problem-Solving (CCPS) model (see Fig. 3-4. Chevalier and Giang, et al., 2020, p.4-7). The CCPS model was built based on both ER activities observation and ER-CT state of the art (see Fig. 3-5).

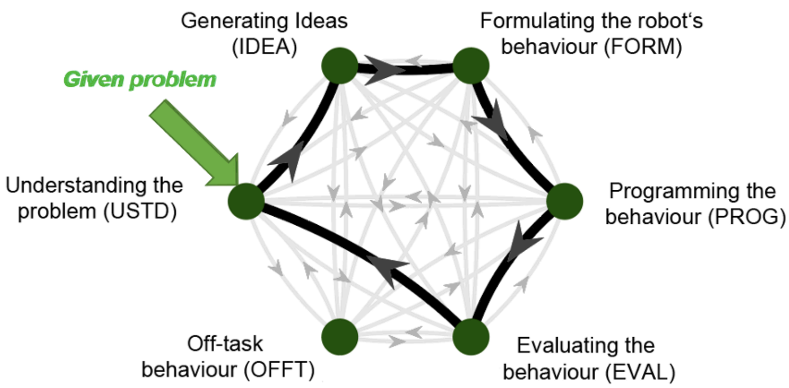

Figure 3-4 The Creative Computational Problem-Solving (CCPS) model.
The 6 green dots are the 6 observable phases, and the black line represents the optimal path to complete the CCPS circle.
The green arrow represents the beginning of the problem-solving situation. This model is iterative.

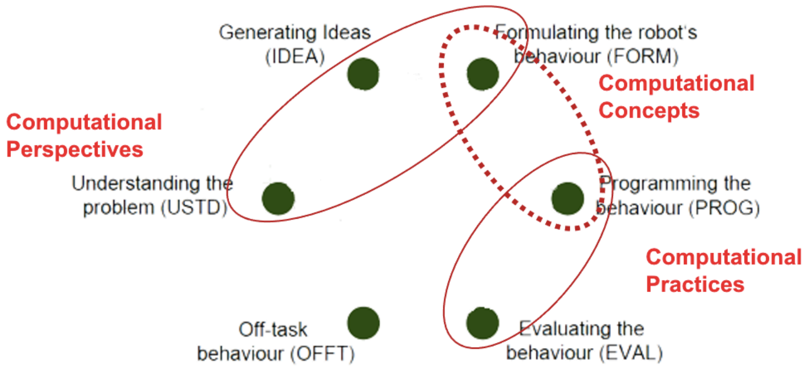

Figure 3-5 The CCPS model and its links with the 3 CT dimensions from Brennan & Resnick (2012).

The CCPS model describes the students' cognitive processes related to the CT competences in ER activities. Compared to other CT models describing the CT facets, dimensions or components (Brennan & Resnick, 2012; Shutes et al., 2017; Romero et al., 2017), the CCPS model or circle is a temporal model of six main states: understanding the problem (USTD), generating ideas (IDEA), formulating the robot's behaviour (FORM), programming the behaviour (PROG), evaluating the behaviour (EVAL) and off-task behaviour (OFFT). The latter is not directly linked to CT competences but rather a reflection of the reality in the classroom. The circle formed by the six states (see Fig. 3-4) is not fixed and linear: there may be as many circles as possible transitions between each of the six states. In addition, the transitions can also be either feed-forwards or feed-backwards. Using this model, the dynamics of student's activity can be traced in an ER situation and thus also the complexity underlying CT competences.

Results of the evaluation study. Subsequently, we tested the CCPS model through the "Thymio Lawnmower Mission". We carried out an experiment with 29 students divided into two groups (Fig. 3-6): the control groups had to achieve the task in a "hands-on approach" (*i.e.,* no intervention by the teacher) throughout the 40 minutes of the mission; the test groups were subjected to the blocking of the programming interface, every ten minutes. However, this latter condition was adjusted in a scaffolding fashion during the task: during the first quarter of the time of the mission by blocking access to the programming interface and then, during the third quarter of the time, by partially blocking it *i.e.,* being able to manipulate the interface but not running any new program (note that the robot keeps the last program in memory and that the pupils could then still observe and evaluate its execution). During the second and last quarter of the time, they had total access to their computer. The summary of the results of this experiment is given in Figure 3-7.

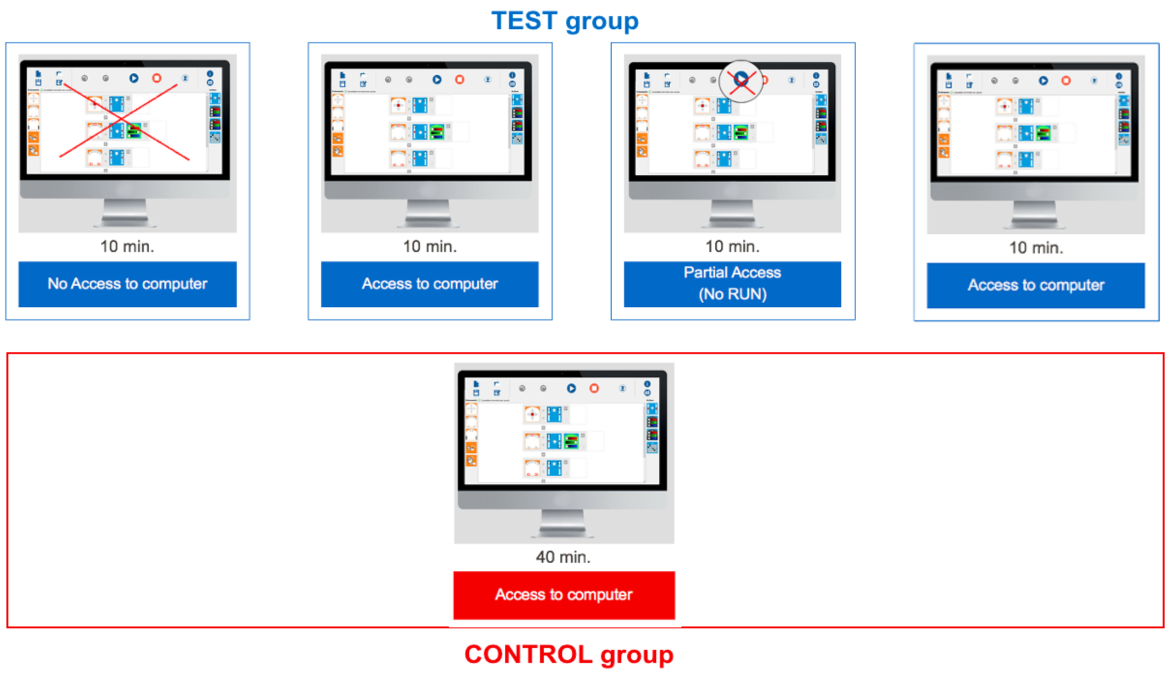

Figure 3-6 Experimental conditions of the two groups running the “Thymio Lawnmower Mission”. Times flows from left to right for the two groups.

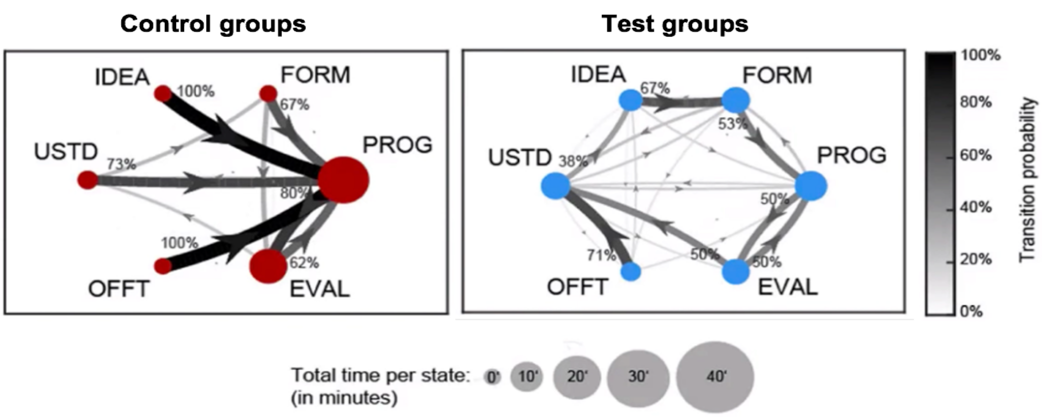

Figure 3-7 Results for Test and Control groups.

Results for Control groups:

Students in the control groups spent two-thirds of their time in the programming and evaluation phases (Fig.3-7). We have thus identified a PROG-EVAL loop (see the red loop in Fig. 3-8) in the CCPS behaviour of the students subjected to no intervention. By repeating this loop over and over again without “re-thinking” their attempts, their probability of getting out of it remained low, as shown in Figure 3-7 (left side). Regardless of the current state, a student in the control group has a chance of going next to the PROG state between 62% and 100%. In addition, the high return rate from the EVAL state to the PROG state (62%) supports this loop. We call this situation a ‘blind’ trial-and-error approach since the student leaves himself/herself little chance of having another behaviour allowing a real debugging (e.g., states like the generation of ideas or formulation of behavior). As a result, the time spent in this blind loop led to two problems:

A) the students did not practice much the other phases of the CCPS cycle, which involve cognitive processes necessary to solve the task (see the green circle in Fig. 3-8), such as:

- the USTD phase involves getting into abstraction, *i.e.,* to "identify and extract relevant information to define main ideas" (Hsu et al., 2018). This phase also involves being able to "decompose the problem" (Shute et al., 2017);
- the IDEA phase, which requires a "creative act" (Duchamps, 1967), *i.e.,* "going from intention to realization";
- the FORM phase, which implies to "organize and model the situation efficiently" (Romero et al., 2017) and to express in the student's language the algorithm, *i.e.,* "the logical and ordered instructions for rendering a solution to the problem" (Shute et al., 2017).

B) Students did not improve their strategy, which led to a series of unsuccessful attempts. As a result, they were less successful in completing the task than the test groups, decreasing their engagement.

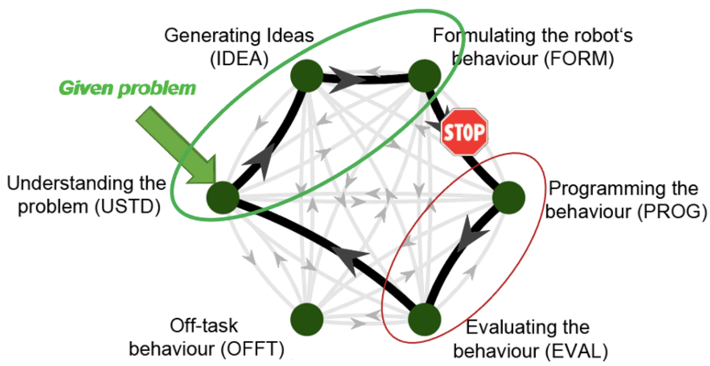

Figure 3-8 The PROG-EVAL loop linked to a "blind" trial-and-error strategy.

Results for Test groups:

1) During the first quarter of the activity, students in the test groups were not allowed to use the programming interface. This "blocking" condition diverted the students' attention from the computer and thus from programming the robot. Instead, students turned their attention to the artefacts in the playground (Giang, 2020), including all the clues within it. It should be noted in particular that the Thymio robot used in the present study has the advantage of signalling to its user any perceived event (*e.g.,* the detection of a wall) by the activation of LEDs (39 in total) (Papadakis, 2020, p.45; Mondada et al., 2017). Such observations of clues picked up by the students may have led them to further exchange and iterate, aided by the feedback inherent in the dialogue that occurs during collaborative situations (Hoyles, 1985). USTD-IDEA-FORM phases were thus involved (see Fig 3-8).

2) During the second quarter of the activity, the experimental condition was released, and students were then given free access to the programming interface. The results showed that students in the test groups had the same appeal to the computer as the control groups (since they also primarily favoured the PROG and EVAL phases, see Fig 3-6). Nevertheless, unlike the control groups, the test groups were enriched by their previous exchanges (on understanding the problem, generating ideas, formulating the behaviour of the robot to be programmed) and were, therefore, more efficient in programming the robot.

3) During the third quarter of the activity, the students in the test groups were again subjected to the "blocking condition", but only partially this time: they had access to the program previously loaded on their robot and to the programming interface, but they could not run a new program. This condition intended to prevent them from entering into what we previously called the blind trial-and-error approach (as with the control groups). As a result, students went back to their previous program, discussed it, and most importantly, attempted to debug it, which is one of the critical components of CT competence (Bers et al., 2014; Shute et al., 2017; Romero et al., 2017). Students worked iteratively on the commonly identified problems and still had to predict possible behaviours because the partial blocking condition prevented them from executing the new program code. Thus, the partial blocking condition allowed students to reflect on their program to identify necessary modifications.

4) In the last quarter of the activity, the experimental condition was released (as in the second quarter). Students in the test groups maintained their engagement in the task: unlike the control groups, no increase in off-task behaviour was observed. Students in the test groups were able to construct a well-established strategy for solving the problem and were able to iterate the theoretically most efficient cycle of the CCPS model (USTD-IDEA-FORM-PROG-EVAL-USTD).

3.2.3 Links with other research and a partial answer to the RQ

With this second paper, we can attempt to answer another part of our main research question. Indeed, we can address the sub-questions stated at the end of chapter 1. We summarize the answers in Table 3.

Table 3 Summary of the different answers to second sub-questions (from paper #2).

Sub-question	Results from phase 2 published in paper #2	Guidelines for designing ER activity
How can the emergence of CT during ER learning activities be modeled?	Based on the analysis of the state of art in Chevalier & Giang et al. (2020): - 6 main CT facets (Shute et al. 2017): problem decomposition, abstraction, algorithm design, debugging, iteration, generalization - CT competences go beyond the limitations on pure coding skills (Wing, 2006) - Before and after programming there are competences involved. The CCPS model is based on the 6 CT states that may iteratively emerge in ER problem solving activity, i.e.: - Understanding the problem (USTD) - Generating Ideas (IDEA) - Formulating the robot's behaviour (FORM) - Programming the behaviour (PROG) - Evaluating the behaviour (EVAL) - Off-task behaviour (OFFT) which is not directly related to CT but has the function of regulating negative emotions (Sabourin et al., 2011)	The development of CT skills with ER should involve students in different phases that occur prior as well as after the creation of programming code. The presence of Off-task behavior (*i.e.,* when students are not involved in the problem-solving process) may be an indicator of a cognitive load for students and, therefore, evidence of a design to be improved.
What intervention methods can foster students' CT during ER learning activities?	In a hands-off approach (*i.e.,* without instructional intervention), students are more likely to use a trial-and-error strategy that would get them into solving the ER problem (outcome). But this strategy may be "blind" and thus not develop CT competences (process). In the CCPS model, fostering students' CT means to support the optimal path of the CCPS circle (and avoid a blind trial-and-error strategy). In this regard, the following 2 interventions can be considered by teachers: - A scheduled blocking of the programming interface fosters cognitive processes related to USTD, IDEA, FORM. - Progressively adjusting the blocking of the programming interface can help students in building a well-settled strategy to approach ER problems and may represent an effective way to provide scaffolding.	Using the blocking access to programming as an intervention method can help teachers fostering students' CT competences during ER activities. Teachers may design and implement an ER activity involving this intervention method. Teachers should be able to use the CCPS model as an instrument for planning their ER activities, as an instrument for intervention during an ER activity and, finally, as an instrument for evaluating the CT strategies developed during ER activities.

During this phase 2, we designed the Thymio lawnmower mission, an ER activity aiming to promote CT and transversal skills such as collaboration, communication. We also designed an instrument to assess the emerging CT in this ER activity: the CCPS model. Thanks to this instrument, it is possible to observe and identify 5 CT states (and 1 residual state, OFFT) in students' problem-solving strategies during an ER activity. Teachers can even foster particular states by using an intervention method such as blocking (totally or partially) the access to programming (other interventions on any transition between two phases would be also possible). This blocking acts as a strategic pause to better reflect and plan what needs to be programmed next. In short, this temporary block serves to give students time to think (in line with the other transversal skill named "reflexive approach"). Its scaffolding in two steps thus leaves room for the teacher's guidance and the construction of the student's autonomy to develop his/her CT.

This intervention method (blocking the transition toward the PROG phase) is one among others, and future work should explore and test other intervention hypotheses in order to demonstrate the more exhaustive validity of the model. Moreover, as the CCPS model's primary goal is to support teachers in the design, implementation, and evaluation of ER activities, future work should investigate whether teachers perceive the added value of the model for their teaching activities.

Based on this second outcome, we investigated whether teachers can effectively take advantage of the model for their teaching activities (see phase 4 in section 3.5). Moreover, other intervention hypotheses were explored and tested in order to demonstrate a broader validity of the model (see phase 3 in section 3.3).

3.3 Phase 3: Improving the ER system to promote CT

With permission of all co-authors, this section is a synthesis of the following article (under review):

Chevalier, M., Giang, C., Laila El-Hamamsy, L., Bonnet, E., Papaspyros, V., Pellet, J.-P., Audrin, C., Romero, M., Baumberger, B., Mondada, F. (*under review*). The role of feedback and guidance as pedagogical interventions to foster computational thinking in educational robotics learning activities for primary school. *Computers & Education*.

As the first author of this publication, my contribution to this work involved: conceptualization, methodology, formal analysis, investigation, data curation, visualization and writing - original draft preparation.

3.3.1 Motivation

We investigated alternative intervention methods to promote CT through ER activities based on the findings and future work reported in paper 2. Using the CCPS model to identify emergent CT states, it was shown in phase 2 that a two-stage intervention (full access blocking, then partial blocking) allows students to develop all CT states in the CCPS circle at the end of the ER activity.

If this two-step intervention considers the teacher's gesture of scaffolding, it does not consider another essential gesture, which is the differentiation of teaching. Indeed, the teacher must be able to vary his or her interventions according to the needs of each pupil. However, in the previous study, the teaching intervention was carried out on all pupils (in the test groups) in the same way and simultaneously. A method of intervention allowing this differentiation, therefore, remains to be studied. It should be more natural, i.e., pulled by the students and not pushed by the teacher: this is a key element in line with the principles of scaffolding and development of students' autonomy. In addition, this method should consider the value of the pause or delay, which forces students to think before acting (in this case, program).

Thus, in this phase 3, we again asked ourselves the following sub-question to answer our main research question: **What intervention methods can foster students' CT during ER activities?**

3.3.2 Main results

Based on the state-of-the-art analysis about how to foster CT in ER, Guidance and feedback were considered as critical intervention methods to foster CT competences in ER settings. A between-subjects experiment was conducted with 66 students aged 8 to 9 in the context of a remote collaborative robot programming mission (a variation of the R2T2 mission[8]), with two levels for each intervention method, resulting in four experimental conditions (Table 4.3). Students worked in pairs and were divided into four sectors (A, B, C, D).

[8] See <https://r2t2-collaboration.com/mars-mission-r2t2/>

Table 4 The four experimental conditions corresponding to the two intervention methods.

	Guidance	No Guidance
Immediate Feedback	C	B
Delayed Feedback	A	D

To further explore the sub-question of assessing CT as a competence, a two-step strategy was employed to report on students' CT competence (both their performance and learning process). Firstly, the students' CT learning gains were measured through a pre-post-test design. Secondly, video analysis was used to identify the creative computational problem-solving patterns involved in the experimental condition that had the most favourable impact on the students' CT score. Results show that students subjected to delayed feedback (without guidance) significantly improved their CT performance ($t_A(15) = -2{,}628$, $p_A = .019$, d de Cohen = 0,68; $t_D(16) = -4{,}381$, $p_D = .000$, d de Cohen=0,94) compared to students subject to immediate feedback (without guidance).

As delayed feedback may appear an effective intervention method for CT development in ER activities, the analysis of the problem solving by the students during the task (based on CCPS model) brings elements to understand such a performance (see Fig. 3-7). Subject to delayed feedback, students are better at formulating the robot behaviour to be programmed, and, thus, such a strategy reinforces the anticipation process underlying the CT competence. As shown in Fig. 3-7, students in sector B were more likely to enter into a "blind trial and error" strategy, whereas students from sector D are more likely to complete a whole CCPS cycle as a strategy. Results show an interaction effect between *guidance* and *feedback* ($F(3, 60) = 2.772$, $p = 0.049$) for « Computational perspective » CT dimension or "Analysis" dimension ($F(1, 62)= 5.32$, $p = 0.024$).

To understand the significant difference between B and D sectors, we analysed the strategies using the CCPS model. Concerning the students undergoing immediate feedback (without guidance) (sector B), the analysis shows they led a Prog-Eval strategy (see left part of Fig.3-9). They completed the task more quickly as immediate feedback allows for quick action and reaction but this modality seems to decrease group communication in favour of action. Moreover, students started to instrument the RUN/STOP with minimalist programs to control their robot remotely. Imeediate feedback seems to generate a dependence on feedback. As a result, students are in the immediacy of the action, which leads to a more reactive strategy.

Concerning the students undergoing delayed feedback (without guidance) (sector D), the analysis shows they led a Prog-Eval strategy like students in sector B, but with intermediate transitions to other phases. Pupils cannot enter this PROG-EVAL loop because it costs them time (30 sec.). During the EVAL phase, they come back to the FORM phase and they verbalise their incomprehension ("but why isn't it moving?") or even anticipate what to do ("you have to move the robot backwards because it might run into the other robot"). They pool their strategies and they seem to (re)negotiate the tasks before pressing the RUN button. As a result, it seems that the delay prevents them from instrumenting Run and Stop buttons. In a word, the ER artefacts coupled with the delayed feedback can trigger a FORM-PROG loop in addition to the already identified PROG-EVAL loop, resulting in a more productive trial-and-error strategy.

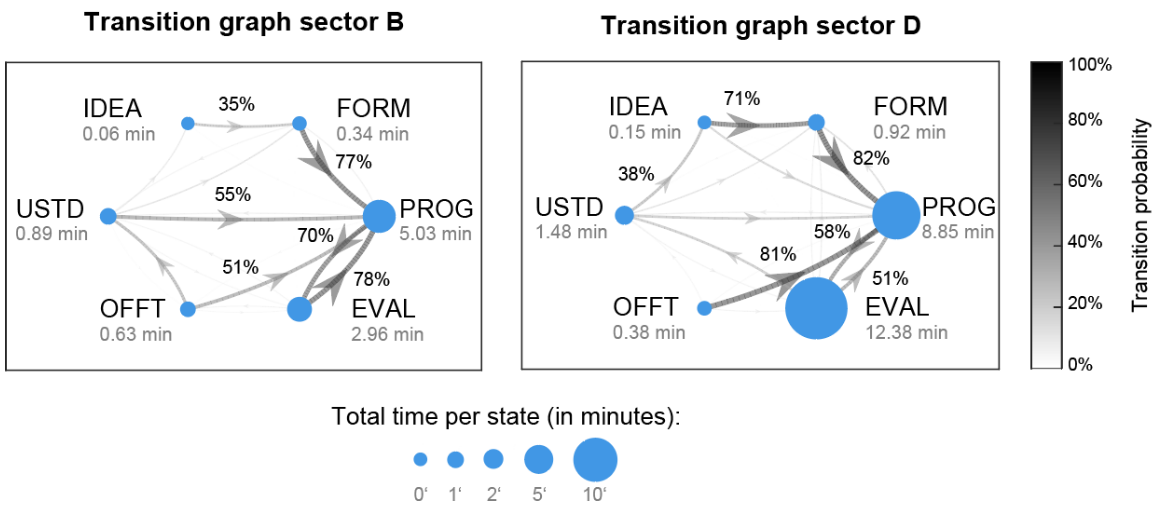

Figure 3-9 CT strategies analysis between sectors B and D during the mission.

Concerning the effect of guidance on problem-solving strategies, results show that students from sector C (with immediate feedback) better decompose the problem and identify the starting position of the robot, *i.e.,* outside the path. Nevertheless, the instrumentation of the immediate video feedback coupled with the affordances of the VPL resulted in an unproductive trial-and-error strategy. Finally, students from sector A (with delayed feedback) led strategies close to that deployed in Sector D. Nevertheless, further research is needed to better understand the issues involved in the interaction between guidance and delayed feedback in sector A. Indeed, the 12 hours of pre-mission instruction may have made the students experts on the type of tasks proposed during the mission. However, as noted by Clark et al (2012), expert students can still learn with minimal guidance. Therefore, the role of guidance at the beginning of the course, when scaffolding is still needed, should be verified in a future study.

3.3.3 Links with other research and a partial answer to the RQ

With this third paper, we can attempt to answer another part of our main research question. Indeed, we can address the sub-questions stated at the end of chapter 1. We summarize the answers in table 4.4.

Table 5 Summary of the different answers to second sub-questions (from paper #3).

Sub-question	**Results from phase 3 published in paper #3**	**Guidelines for designing ER activity**
What intervention methods can foster students' CT during ER learning activities?	Based on both perspectives (the process and the result), we analysed the impact of delayed visual feedback and guidance on the development of the students'CT competence in an ER task. We found out that: - The presence or absence of guidance (mediated by a worksheet with questions) has no significant impact on student learning. - Delayed feedback helps foster CT, in particular “computational perspectives”. - Delayed feedback’s benefits seem to stem from students spending more time reflecting on the task.	The delayed feedback can be implemented in an ER learning activity to foster the computational perspective dimension of CT. It can be handled by the artefact setting, thus freeing the teacher to perform other tasks with the students.

In this phase, we were able to find and test another intervention method that could foster the CT competences of the students. Nevertheless, if the CCPS model and intervention methods have shown convincing results in phases 2 and 3, it is still necessary to submit these tools to teachers in order to evaluate them, *i.e.,* to validate their usefulness, usability and acceptability with them. This was the purpose of the last phase of this thesis work.

3.4 Phase 4: Teachers' perspective on fostering CT through ER

With permission of all co-authors and giving the pre-print version of the paper, this section is a synthesis of the following article:

Chevalier, M.*, El-Hamamsy, L.*, Giang, C., Bruno, B., & Mondada, F. (2021). Teachers' perspective on fostering computational thinking through educational robotics. *arXiv preprint arXiv:2105.04980*.

**both first authors*

This paper is published by Springer with the following reference:

Chevalier M., El-Hamamsy L., Giang C., Bruno B., Mondada F. (2022) Teachers' Perspective on Fostering Computational Thinking Through Educational Robotics. In : Merdan M., Lepuschitz W., Koppensteiner G., Balogh R., Obdržálek D. (eds) Robotics in Education. RiE 2021. Advances in Intelligent Systems and Computing, vol 1359. Springer, Cham. https://doi.org/10.1007/978-3-030-82544-7_17

As one of the two equally contributing main authors of this paper, my contribution to this work involved: conceptualization, methodology, formal analysis, investigation, data curation, visualization and writing - original draft preparation.

3.4.1 Motivation

Based on phase 1, it was highlighted that teachers need tools and resources to implement CT in an ER context. In phase 2, we built the CCPS model that we tested in phases 2 and 3. As any model is an abstraction and may therefore be considered impractical and unimplementable by teachers, we thus carried out a training with teachers to know whether they can effectively take advantage of the CCPS model for their teaching activities.

Therefore, in this last phase, we aimed at answering the following subquestions: **How do teachers perceive the ER-CT model and the ER learning activities fostering CT?**

3.4.2 Main results

In order to raise the point of view of the teachers about the CCPS model and our designed ER learning activity (the Thymio lawnmower mission), we based our research method on the three dimensions of the computer-based learning environment assessment from Tricot et al.'s framework (2003). A study was conducted with 334 teachers participating in the EDUNUM mandatory training program (for Digital Education underway in the Canton Vaud, Switzerland). During the ER training session, the teachers participated in the autonomous lawnmower activity mediated by the CCPS model. The teachers worked in groups of 2 or 3 to collaborate and co-construct. Similarly to the study in phase 2, a temporary blocking access to the programming interface was implemented at regular time intervals (so that teachers understand how the CCPS model can be used to mediate an ER learning activity). While our sample did not know the concept of "computational thinking" - since it was not yet written into the curriculum - we probed them about the transversal skills involved in the ER activity they tested. We also probed them on what they perceived as the most appropriate artefact to foster each CCPS phase (see Fig. 3-8).

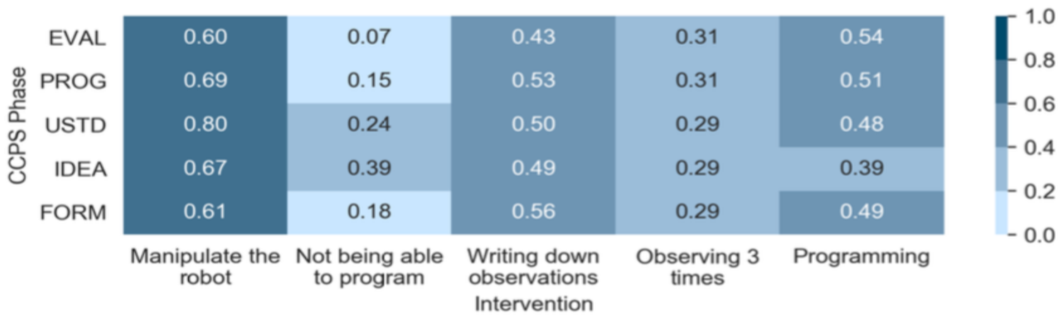

Figure 3-10 Teachers' perception of the most appropriate intervention methods to foster each different phase of the CCPS model. For each phase of the model and intervention method, the proportion of teachers having selected the approach as relevant is shown.

According to teachers, the ER learning activity with the Thymio robot is useful to engage in transversal skills, except for creative thinking which is less perceived by teachers. This result is important, here with our sample made of beginners, because it validates the link between transversal skills and ER that was identified in the phase 1 study with pioneer teachers. This suggests that the use of the CCPS model in designing ER learning activities helps teachers see and strengthen the link between ER, transversal skills and CT. Still concerning utility, we aimed at Teachers' perception of the link between intervention methods and the different phases of the CCPS model. The most relevant artefacts for all the phases of the model is the possibility of manipulating the robot, thereby reinforcing the role of physical agents in fostering CT skills. The second most popular choice was to write down the observations, likely because this constitutes a means of specifying what happens with the robot in the environment. The written observations then become a "thinking tool" that supports modelling and investigation. Surprisingly, and although the teachers were introduced to the fact that unregulated access to the programming interface tends to lead to trial and error behaviour, programming was more often selected than "not being able to program". This suggests that teachers rely more on what they have experimented during the training session than on what the CCPS model suggests to them.

In terms of the usability (Sub-RQ#2), teachers perceived how they could design an activity and intervene using the CCPS model (80%), but were less able to perceive how the model could be used to assess where the students were in terms of learning and regulate the activity to mediate their learning.

Concerning the acceptability of the model (in terms of intent to use it), we can note progressive levels of appropriation: between the teachers who might be willing to conduct the same ER learning activity in their classrooms (64%), those who are willing to adapt the activity (40%), create their own custom one (32%), and conduct a more complex one (20%). One can put this in relation with the Use-Modify-Create (UMC) progression (Lytle et al., 2019) which was developed to scaffold student learning in CT contexts:

- Teachers start by using the model in a given RE learning activity to gain self-efficacy.
- Only then will they feel comfortable adapting the use of the model to their teaching style and to individual students.
- Finally, teachers will reach a level where they create their own instructional interventions of RE to foster CT skills.
- It should be noted, however, that intention is likely to be influenced by external factors (e.g., time or access to robots, which are common barriers to the introduction of RE in formal education).

3.4.3 Links with other research and a partial answer to the RQ

With this fourth and last paper, we can attempt to answer the last part of our main research question. Indeed, we can address the following sub-questions stated at the end of section 2. We summarize the answers in Table 4.5.

Table 6 Summary of the different answers to second sub-questions (from paper #4).

Sub-question	**Results from phase 4 published in paper #4**	**Guidelines for designing ER activity**
How do teachers perceive the ER-CT model and the ER learning activities fostering CT?	According to the teachers, the CCPS model is: - Useful partially for the transversal skills (the activity design and intervention methods employed are considered more useful); - Usable for planning and intervening during an ER learning activity but less for regulation and evaluation; - Acceptable with progressive levels of appropriation.	To help teachers implement ER learning activities in the classroom and gain autonomy to create their own activities that foster CT skills, it seems relevant to alternate between experimentation in classrooms and debriefing during teacher training and go beyond providing pedagogical resources.

Chapter 4 General Discussion

The aim of this thesis was to investigate the mediation of CT using educational robots to answer the following research question (RQ): **How can teachers implement educational robotics (ER) learning activities to develop the students' computational thinking (CT)?** In order to contribute to the state of the art and attempt to answer this RQ, the investigation was conducted in four phases by probing key stakeholders, and developing and validating an ER-CT model, in order to answer the following sub-questions (Sub-RQ#1 to Sub-RQ#4):

1. How do teachers perceive the use of a robot in their classroom?
2. How can the emergence of CT during ER learning activities be modeled?
3. What intervention methods can foster students' CT during ER activities?
4. How do teachers perceive the CCPS model and the ER learning activities fostering CT?

The first study (Chevalier et al., 2016) highlights that teachers having followed a teacher training program have a globally positive attitude towards robotics (Sub-RQ#1), notably in terms of utility and acceptability, and this regardless of whether or not they have prior experience with robots in their classroom (*i.e.,* with students). Indeed, teachers perceive ER as useful to promote 21st-century skills (literacy skills and transversal skills such as creative thinking, collaboration, reflective thinking), thus echoing the findings of other ER studies, both prior and subsequent (Nugent et al., 2010; Eguchi & Uribe, 2012; Ardito et al., 2014; Romero & Dumont, 2016; Theodoropoulus et al., 2017). Training teachers thus constitutes a first step towards the instrumentation (Trouche, 2003) and appropriation of educational robots by teachers, helping them familiarise with the tool at their disposal. However, and despite the teachers being already motivated by robotics, there are certain barriers that prevent them from passing to the second stage of instrumentation, and thus employing ER in their practices. Specifically, a negative attitude towards ER tends to appear in relation to their usability (and therefore appropriation), due to a lack of time, training and resources, as confirmed by Kradolfer (2014) and Negrini (2020). As acceptability is correlated with the perceived usability of robots, by improving the usability of the robot (through in-service training and adapted learning activities), teachers' acceptability should improve. Therefore, to ensure that teachers' perception remains globally positive and that teachers appropriate ER (first instrumentation) and are prepared to orchestrate ER learning activities that foster CT (second instrumentation), one must ensure its usability by teachers. High stakes are at play by failing to do so and thus failing to facilitate the introduction of ER into teachers' practices as CT will also suffer as a result from the lack of diverse approaches to teach it (Shute et al., 2017).

Research can contribute to reaching the second stage of instrumentation by developing adequate resources (Sullivan et al., 2017) to facilitate the introduction of ER into classrooms. This was the objective of Chevalier & Giang et al. (2020) and Chevalier et al. (2021). Indeed, while there are numerous CT activities at teachers' disposal in the literature, among which numerous ER activities, these are not sufficiently well guided and detailed for usage by teachers (Atmazidou et al. 2012; Lye & Koh, 2014), and thus not implementable in classrooms. Still motivated by the translational research approach, it was then necessary to create robotics activities (and artefacts) that are adapted to teachers' needs (and thus must be linked to the 21st-century skills, as shown in Chevalier et al., 2016), as well as the tools to evaluate them (assessments), all the while keeping in mind the learning objectives (fostering the full range of CT competences), and the intervention methods to achieve said objectives, in accordance with the principles of constructive alignment (Giang, 2020). In Chevalier & Giang et al., 2020) and Chevalier et al. (2021), the necessary characteristics of an ER learning activity which fosters 21st-century skills, and thus CT, were specified and employed in the development of two complete ER learning activities: the Thymio Lawnmower (Chevalier & Giang et al., 2020), and an adapted version of the R2T2 mission. The two developed ER learning activities employed the CCPS model (Sub-RQ#2) which was first presented in Chevalier & Giang (2020) as a model 1) for the design of intervention methods prior to the activity, 2) which renders CT observable during the activity by expliciting the cognitive processes in play in CT problem solving settings (Chevalier & Giang et al., 2020, Chevalier & Giang et al., 2021), thus contributing to the gap identified in the CT assessment literature (Zhong, 2016). Indeed, both quantitative (MCQ with items aiming at the 3 CT dimensions) and qualitative (through the indicators of the 6 phases CCPS phases) assessment were carried out in order to better judge CT as a competence.

As recommended by Lye & Koh (2014), two intervention methods were investigated to foster both computational practices and perspectives. These pertained to the introduction of delays in order to encourage students to spend more time "thinking" and less time "doing" (Sub-RQ#3) but differed in how the delay was mediated and on which phase of the CCPS model it acted upon. The first intervention method (Chevalier & Giang, 2020) was mediated by the teacher through the introduction of a manual blocking access to the programming interface, and prevented a transition to the programming phase. The second intervention method (Chevalier & Giang et al., 2021) was mediated by the artefacts through an inherent delay in the system between the moment the program is launched and the moment one can see its execution. This inherent delay makes it costly for students to run the program as they must wait for 30 seconds, thus encouraging them to spend more time thinking before executing their program. Both approaches to the introduction of delays proved successful with respect to the development of students' CT perspectives and practices by ensuring that students went through the entire CCPS cycle, as shown in Chevalier & Giang (2020) and Chevalier et al. (2021). Additionally, these studies show that the choice of intervention method not only has an impact on the development of CT competence, but also on teachers' classroom management. For example, having a delay mediated by the artefacts frees up teachers to perform other tasks with their students.

In sum, Chevalier & Giang et al. (2020) and Chevalier et al. (2021) put forth the three main contributions of the CCPS model:

1) while inspired by existing theoretical CT models (Brennan & Resnick, 2012; Romero et al., 2017; Shute et al., 2017), the CCPS is an operational framework (Ioannou and Makridou, 2018);

2) that renders CT observable, thus helping validate the utility of specific intervention methods;

3) and making a distinct contribution regarding the transfer to classrooms by providing teachers with explicit guidance regarding interventions (with the delay factor), as recommended by Atmatzidou & Demetriadis (2016).

The final step thus required verifying teachers' perception of the complete ER learning activity, that is to say their perception of the associated artefacts, assessment, and intervention methods (Sub-RQ#4). The analysis of teachers' perception in a teacher training program (Chevalier & El-Hamamsy et al., 2021) showed that they believed the complete ER learning activity was useful to foster 21st-century skills, thus satisfying the utility criterion expressed by teachers in Chevalier et al. (2016). However, it is not clear for teachers how the use of the artefacts (usability) is related to the underlying strategy employed by students to solve the problem (Kalmpourtzis & Romero, 2020). This means that teachers are not yet capable of mediating ER activities in order to foster the full range of CT competences (*i.e.,* not just concepts, but also practices and perspectives). Nonetheless, the teachers believe they are able to employ the CCPS model to plan and intervene in ER learning activities, but are unable to fully appropriate the model in order to assess student learning and regulate their teaching accordingly. This shows that teachers are not yet at the second stage of instrumentation (Trouche, 2003) when it comes to mediating CT through ER. This is likely because present teacher training programs are insufficient to help teachers understand how to foster CT: teachers need more time, both to reach the first stage of instrumentation and to appropriate the models and methods that they must master to foster CT in ER problem solving settings (second stage of instrumentation).

Hence, in order to implement educational robotics (ER) learning activities in the classroom to develop students' computational thinking (CT), does this mean that teachers' training time needs to be extended?

While time is obviously a key factor, it is not the only issue. The organisation of teacher training, like the time spent by students in class, must take into account the two stages of instrumentation (Trouche, 2003): firstly, it is necessary to train teachers (like students) in ER artefacts, learning activities and the CCPS model; secondly, it is necessary to support teachers in projecting themselves into the classroom (with their students) so that they can construct ER references concerning problem-solving situations.

The implication, from a research perspective, is that more work needs to be done to facilitate the appropriation of the said models and methods (of intervention and assessment), for example by developing more explicit guidelines that would ensure that all teachers, not just the pioneers who are more accepting of ER (Chevalier et al., 2016), can employ ER to foster CT. These guidelines should focus on CCPS observables. Indeed, as experienced by the evaluators in the second article of this thesis, teachers need to be trained to observe what happens during CCPS. Thus, during teacher training, the second phase of instrumentation should focus on the indicators and observables that enable the phases of the CCPS model to be identified. In this way, the teachers will more easily appropriate the CCPS model but they will also be equipped with the indispensable parameters allowing them to evaluate the CT competence of their students in action and in situation.

Finally, it remains that the problem-solving tasks proposed in our research are generic (or even canonical, such as following a line or exiting a maze). As a consequence, a didactic effort is now needed to define a range of problem situations allowing to vary the complexity in the development of CT in an ER context.

Chapter 5 Conclusion

5.1 Achieved results

In conclusion, the contributions of this thesis to the state of the art consists in the following elements:

1) The creative and computational problem solving (CCPS) model, an operational ER-CT framework that was developed over the course of the thesis for the purpose of designing ER-CT learning activities, and more specifically the associated intervention and assessment methods, by rendering the CT strategies of students observable.

2) The design and analysis of two complete ER learning activities looking to promote the full range of CT competences based on the CCPS model, including the artefacts, assessment and intervention methods satisfying the requirements of constructive alignment (Giang, 2020).

3) An example of a solution to overcome the unproductive trial-and-error strategy, with the "delay" identified as an impacting factor on the developpement of CT competence.

4) This thesis work also addressed the 4 recommendations of Lye and Koh (2014) on CT by:

   - Exploring a classroom-based intervention,
   - Focusing on computational practices and computational perspectives,
   - Examining the programming process,
   - Analysing qualitative data of students.

5) The identification of three main instructional functions of the CCPS model helping teachers to mediate CT through ER in their classroom:

   - **Before the class: to plan** an ER learning activity aiming at fostering CT. Depending on the CCPS phase to foster, teachers can plan an intervention in the ER learning activity (such as a temporary blocking access to the programming interface).
   - **During the class: to identify** in situ (i.e., during an ER activity) the cognitive process activated by the students while solving a creative and computational problem. Thanks to that identification, teachers can then intervene to help students depending on the CCPS phase they are in (and therefore their proper needs).
   - **After the class: to assess** the development of the CT cognitive process.

6) The following recommendations for training sessions on "how teachers can mediate CT through ER learning activities" considering the 2 steps for instrumentation (Trouche, 2003):

- **First step** should help teachers appropriating the tools *i.e.*, the ER artifacts, the interventions methods, the CCPS model (and its observables).
- **Second step** should help teachers organizing the constructive alignement for ER learning activities (Giang, 2020) between its 4 components:
  - **Intended outcome** should aim at one of the 3 CT dimension defined by Brenan and Resnick's model (2012) or by Romero et al.'s model (2017) which has a finer granularity (into 6 CT components). In addition, one should tend to aim at 21st-century skills such as collaboration, communication, creativity.
  - **ER artefacts** should be considered a prerequisite for the CCPS task. A period of learning about the functionning of the machine and its programming interface (computational concepts) is necessary before any problem can be solved.
  - **Instruction** should integrate delay as an intervention method favouring thinking before doing, i.e., fostering the computational perspectives dimension of CT as well as the computational pratices dimension.
  - **Assessment** of the CT competence should be considered both from the point of view of performance (and measured using a MCQ-type test) and from the point of view of the strategies deployed in action and in situation, during the CCPS process. For this purpose, teachers need to be trained on how to observe students during the CCPS phases (based on observables provided by the CCPS model).

It is through this training effort that teachers will eventually be able to plan ahead of the interventions, and with the help of the CCPS model, the problem settings and the pedagogical interventions, all the while considering their relation to the artefact affordances.

5.2 Limitations and Future work

A first limitation of the research is linked to the nature of a competence (as defined in chapter 1). Indeed, we have shown that most CT phases can be observed (by gestures or words) such as PROG (with screencasting) or EVAL (with video feedback). But other CT phases are not easily observable. This is the case of the "IDEA Generation" phase which should be addressed through a theoretical framework dedicated to creativity.

Nonetheless, we have shown that by acting on the design of the activity (by a specific intervention) it is possible to bring out what is going in the student's mind. Therefore, future work should investigate other intervention methods and artefacts that can foster the whole CCPS cycle. Such methods should be systematically tested among teachers and their students in real classroom settings, and should result in specific and concrete guidelines for teachers.

A second limitation is due to the research approach used in this thesis work. Indeed, the translational research approach presents a specific difficulty: the problem of adoption. Indeed, in our last phase, we were unable to remove the barrier of understanding among the participating teachers. We indeed experimented the limit of such an approach because "it is not enough to have proven that a given practice is more effective, it is also necessary to convince the target audience to adopt it" (Dehaene & Pasquinelli, 2020, p.16).

Therefore, future work must take into account the new obstacles or levers to adoption that are emerging as we go along in the hot topic of introducing digital technology into school. The translational research approach allowed us to link the CCPS model to classroom practice from the perspective of both teachers and students. Indeed, the back and forth between induction and deduction allowed us to self-feed our approach giving us perspectives for future work such as the investigation of other intervention methods, like guidance, and artefacts that can foster the whole CCPS cycle. In order to know how to guide, it is necessary to know the typical errors, which implies defining typical tasks and problems in ER to foster CT. Thus, the teacher's role during an ER learning activity, using the CCPS model, may help to define new artefacts but also a range of ER task fostering CT.

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Appendices

Paper #1

Chevalier, M., Riedo, F., & Mondada, F. (2016). How do teachers perceive educational robots in formal education? A study based on the Thymio robot. *IEEE Robot Automation Magazine*, 23(2), 16-23.

How do teachers perceive educational robots in formal education? A study based on the Thymio robot*

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I. INTRODUCTION

Robots have generated interest in schools since Seymour Papert's works; however when his Logo turtles were introduced into schools in the 1980s, they proved to be unreliable, expensive, and limited [1]. Since then, we have seen various affordable, reliable, and polyvalent platforms such as Lego Mindstorms [1] or the Bee-Bot [2]. Robotics has become more appealing, and it is an established fact that educational robots can improve children's motivation [3], [4]. Robotics also embodies a wide range of disciplines, which allows its use in a broad educational area and in interdisciplinary studies. Its use in compulsory schools could bring technology to a larger audience, including both genders.

Although there has been an increasing number of extra-curricular robotics activities such as robotic contests or festivals [5], which show the widespread adoption of robotics in informal education, several authors are struggling to understand why robots are still underused in schools, for formal education. Some argue, without clear evidence, that this is due to the lack of material available for teachers [6], missing functionalities [3], a paucity of flexibility and dynamism in schools [7], or a dearth of evidence regarding the educational benefits of this approach [4]. Although there is no agreement over the exact reasons for this situation, it seems clear, from these and other studies [8], [9], that teachers play a key role in the introduction of technology in schools. Despite this obvious observation, there is a severe lack of studies analyzing this key factor, and, in particular, the attitude of teachers toward educational robots. Lee et al. [3] examined the perception of such robots in Korea, by teachers, students, and parents. Their results showed that, while the teachers' opinions of robots were worse than those of the students and parents, none of them wanted robots to replace teachers. Fridin and Belokopytov [8] studied the first-time acceptance by teachers of a socially assistive humanoid robot, showing that teachers' desire to use robots is mainly linked to their perceived utility as tools. A limiting factor in this study is that the teachers were interacting with a robot for the first time. Kim et al. [9] performed a short survey of 116 Korean teachers who had had an initial experience of using robots in education, asking them about their opinion on the potential use of this technology. The results indicated that the teachers considered this technology appropriate for use from the fifth grade onwards, and applicable to almost every discipline but particularly useful for including introverted children in class activity. This study, which looked at elementary, middle, and high school teachers, still lacked a more detailed analysis of the specific motivation behind this choice. Kradolfer et al. [10] conducted a deeper analysis, using sociological methods to understand the blocking factors in the use of robots by teachers who were already familiar with this technology. They came to the conclusion that such limitations could be a result of the high price of robots, the absence of either institutional injunctions or pedagogical research in educational robotics, or the scarcity of appropriate materials and teacher training.

In the French-speaking part of Switzerland, several efforts have been made to address these issues: The development of the affordable Thymio robot [11], its widespread distribution (more than 2000 units) to schools, the production of associated educational material, the documentation of best practices in order to help teachers understand the benefits, and training programs for them on the use of Thymio. This framework has allowed for the observation of a broad spectrum of situations relating to the application of, and reactions to, robots in formal education. To systematically analyze this process, we ran a survey targeting three key factors: utility, usability, and acceptability. The teachers' feedback on these three aspects and their mutual influences has brought about a better understanding of the mechanisms underlying the introduction of robotics in schools.

II. SCOPE OF THIS SURVEY

A. Opportunity

Since 2013, the Ecole Polytechnique Fe ́de ́rale de Lausanne (EPFL), in collaboration with the Lausanne University of Teacher Education (HEP-Vaud), has offered training sessions for teachers of the first, second, and third cycle (corresponding to pupils from 4 to 15 years old) of the French-speaking part of Switzerland. The purpose of these sessions, named "Robots en Classe", is to train teachers interested in the principles of educational robotics, to show the links between them and the official curriculum (PER, Plan d'Etudes Romand), as well as to create a network for these teachers. 214 teachers attended at least one of the training sessions in 2013 and 2014. We asked those who agreed to fill out a survey and answer our questions. The aim of this study was to learn what they perceived as the benefits of using robots in teaching. In particular, we asked them about their opinion of the pedagogical use they make, or intend to make, of robots. This questionnaire focused on the Thymio robot that was presented in the training sessions.

B. The Thymio Robot

Teachers can take advantage of the wide range of educational robots available on the market, each of which has specific features due to the choices made by the designer. For the purposes of this study, we will focus on small-wheeled systems, as they are the most commonly used types for education and correspond to our choice with Thymio.

The most widely used and studied [12] system is clearly the LEGO® Mindstorms kit [1], now available in its most recent model known as EV3. The design choices made by LEGO® include the key role of construction, a very technical look, a high price compared to the competitors, and the decision not to support LINUX as a platform but to enable the use of tablets. The resultant product is ideal for 10+ year-old boys. Although the construction using LEGO® bricks is known as a fantastic activity for children, it also requires that students must build the robot before seeing it working, which impacts their motivation, and entails a great deal of effort on the part of teachers, who have to ensure that all sets include all pieces at all times. To reach younger users, LEGO® is selling the WeDo® system, which is much cheaper but with very limited input-outputs.

Some platforms, such as Edison1 or Dash & Dot2, feature LEGO®-compatible connectors to enable construction on top of a ready-to-use robot. Edison’s design choices are based on extremely low-price solutions, making the whole product very affordable (49$) but also very limited in its functionalities and performances. The Dash & Dot design is more oriented towards being a very nice-looking toy for children aged between 5 and 15, with two different robots. Technically, these systems have a limited set of sensors, but they display impressive behaviors, combining sound, movement and light effects in an attractive manner. On a tablet, the child can intermix a large set of attractive pre-defined behaviors, ensuring highly entertaining results.

Kibo[13] and BeeBot3 target younger children by focusing on tangible interaction, avoiding the use of computers or tablets. BeeBot is very affordable and has no sensors. The children can program its movement on a grid using arrows on its back. Its bee-like appearance is attractive for young children. Kibo is much more expensive as it is produced in small quantities, but it can be programmed without a computer using a set of wooden blocks equipped with bar codes that can be scanned to compile the robot program.

At the other end of the scale, a large number of robotic products allow the user to have direct contact with electronics. Several of them are linked with well-known processor boards, such as Arduino4 or Raspberry PI5. A good example of such products is mBot6, which is based on a simple frame with a couple of sensors and an Arduino board. The choice of mass-produced electronics allows for a lower price, but results in a less integrated product.

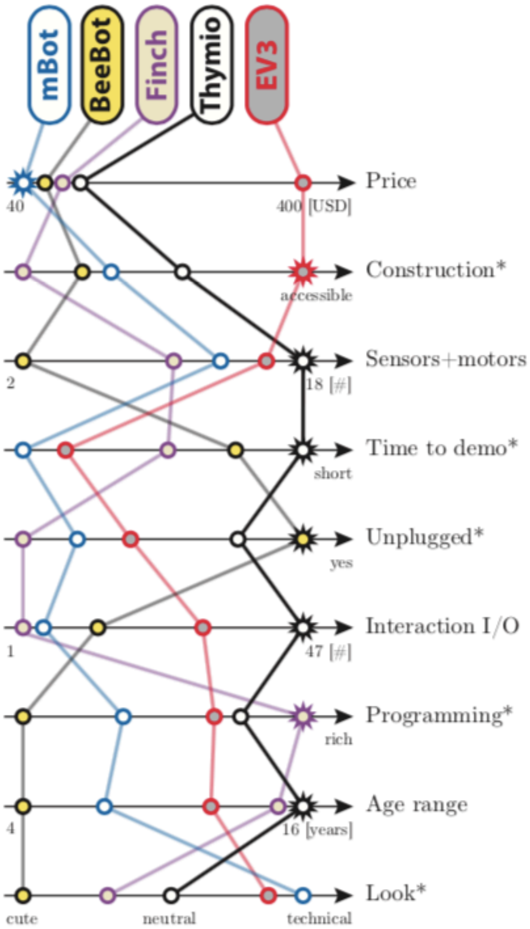


Fig. 1: Profile of some key features for a set of well-known educational robots mentioned in the text. These features are the price, the support and accessibility of construction activities, the quantity of exteroceptive sensors and motors, the time needed to get a demo running after unpacking the robot, the number of devices supporting interaction, the programming possibilities, the width of the age range of users, and the look, where we distinguish technical-looking robots from cute robots, with a neutral look in the middle. For the age range, when the upper limit is not applicable (for instance, 10+) it was artificially set to 20. In modular systems were several motors or sensors can be connected on a fixed number of input/outputs, this has been multiplied by a factor two. Also for the number of devices supporting interaction, we counted all single devices excepted screens, considered artificially equivalent to 20 single devices. Some features are quantified and their axis is labeled, while others are qualitative estimations and are labeled with a (*). The features characterizing a specific product are highlighted by a star. Each of the robots has at least one aspect in which it excels, which was one of the criteria of selection for the robots appearing in this graph.

Fig. 2: Thymio II (Photo by Gordana Gerber).

Finally, there are several robots, such as Finch7, that are fully programmable but have very limited interactivity with the user. The Finch design, for instance, includes some classical sensors, a color LED, and a differential drive system, but has a highly reduced user interface. Finch's specific feature is that it is constantly tethered, removing the need for a battery and simplifying the communication. In addition, this approach allows the user to control the robot from the computer, where many programming environments are available.

When robots are programmed from a computer or tablet, the programming user interface is a crucial element of the system. There are two main approaches: text and graphical programming [14]. Graphical programming is considered to be best suited for beginners, while text programming is more flexible and powerful. The most well-known graphical programming environments, besides the LEGO one, are Scratch and Blockly [14].

Our work is based on the Thymio II robot. Thymio II, hereafter referred to as Thymio, is a small mobile robot designed at EPFL in 2010-11 (see Fig. 2). It is intended as an affordable platform for both schools and individuals, allowing the discovery of basic notions of robotics and computer science.

Thymio is a complete robot, that is usable out of the box thanks to pre-programmed behaviors that illustrate the use of the different sensors and actuators. On its shell and on the wheel, it has LEGO-compatible fixations to allow construction. In contrast to all other products discussed, Thymio has a very neutral look; all white and with a very clean but functional shape. This makes Thymio highly gender- and age- neutral, as shown in previous studies [11]. Thymio features a wide range of sensors (nine IR proximity sensors, a three-axis accelerometer, a microphone, a temperature sensor, a remote-control receiver, an SD-card slot, and five capacitive buttons) as well as two motors, a loudspeaker, and 39 LEDs spread all over its body. These LEDs constitute another highly unique feature of Thymio: a high interactivity with the user, for instance displaying all sensors activity in real-time on the robot body. In addition to a set of pre-programmed behaviors, Thymio runs an Aseba Virtual Machine which can receive the user's code. Aseba offers three programming interfaces: a text-based one to input Aseba scripts directly, a Blockly interface where code is represented by graphical blocks, and VPL, a visual programming language that is more accessible for beginners [15], even including non-readers. A unique feature of these environments is that they are linked together. Therefore, a child can program with VPL and then observe the corresponding text script. This feature has been very well received by the teachers, as it enables a smooth approach to programming. Finally, Thymio is highly popular due to its very simple logistical requirements, especially in comparison to Mindstorms, as well as because of its affordable price. The main criticism to date is that Thymio is incompatible with Scratch, the most common programming interface among beginners; however, this issue is very close to being resolved. Thanks to these factors, Thymio is gaining popularity in schools, and efforts are ongoing to improve it by including a wireless module and the use of augmented reality in the programming interface [16].

A comparison between five of the most well-known educational robots, based on a set of key features, is given in Figure 1. The specific advantages of each platform are highlighted by a star on the corresponding axis. This shows that construction-based robots require a lot of effort before being operational, lack the possibilitiy of being used in unplugged activities, and are less interactive. Cheaper robots with few or no sensors, such as the BeeBot, can be more effective in unplugged activities and are quickly operational. Thymio shows a very interesting profile, with a neutral look and a set of features combining those of the other systems, excepting the exceptional construction possibilities of the LEGO EV3 system.

C. Research Questions

The literature concerning educational robots often focuses on their effect on pupils [12]. Reports on teachers' reactions to the phenomenon are thinner on the ground. There is a greater selection of literature concerning teachers' practices within Information and Communication Technologies (ICT). For instance, according to the PROFETIC study published in 2012 by the French National Education [17], 97% of French teachers consider ICT useful in class, but only 5% actually use them daily. What about educational robotics? Do teachers consider it useful, and do they actually use it in class?

In this study, we will try to understand why teachers use Thymio. We propose to measure the teachers' perception of themselves and of their environment as they use Thymio. To this end, the following questions were posed:

- What do they perceive as the robots' main utility?
- What kind of knowledge do they target in robot-based activities? In which school subjects are involved?
- What professional skills are required to use the device? How is the use of robots facilitated?
- What is the perceived usability of the device? Can it be easily handled by the pupils?
- What is the perceived acceptability of integrating this type of device in teachers' practice? What are the constraints of the device in classroom use?

D. Methodology

If we consider robots as being part of ICT, we must therefore evaluate educational robots in the same way as we would evaluate a computer-based tutoring system. Accordingly, we started from Tricot's approach, which considers all possible relationships using three dimensions [18]:

- *Utility* measures the conformity of the purpose of the device with the users' needs: does the device allow the teachers to reach their teaching goals?
- *Usability* measures the ease of use and applicability of the device: can the device be easily handled by pupils? What are the constraints of use in the classroom?
- *Acceptability* measures the possibility of accessing the device and deciding to use it, the motivation to do so, and the persistence of use despite difficulties: is the device compatible with the teacher's practice, resources, constraints, and objectives?

To measure the acceptability of the device, we merged this model with that of Deci & Ryan [19], concerning motivation. More specifically, we used Vallerand's test, which presents 7 types of motivation [20]. Note that we did not consider amotivation, which is "the state of lacking an intention to act" [19]. As Kradolfer showed [10], it is difficult to find teachers who are explicitly amotivated. Moreover, our pool of respondents displayed their motivation by subscribing to the training sessions. We will characterize motivation as follows:

- *Intrinsic motivation* refers to doing an activity for its own sake or for the pleasure we feel doing it. Here, this motivation can be linked to *knowledge* (with the goal of learning something new), *accomplishment* (with the goal of being efficient and skilled), or *stimulation* (without a clear goal; for the sake of the activity itself).
- *Extrinsic motivation* refers to doing an activity for reasons external to this activity. This motivation may or may not be *self-determined*. In the first case, it means that a choice is made, even though the activity is not done for pleasure (*regulation through identification*). In the second case, the activity is done because of external pressure (in *external regulation*, this pressure is initiated and maintained by factors external to the person, while in *introjected regulation* it is generated by the person, without being fully acknowledged).

TABLE I: Age and gender of the respondents

Age group	Women	Men	Total
20-29	0	0	0
30-39	7	3	10
40-49	13	6	19
50-59	7	4	11
60+	1	2	3
Total	28	15	43

TABLE II: School level of teachers participating in the survey

Group of teachers	Teaching children aged 4 - 8	8 - 12	12 - 15
Teachers who had already used Thymio	5	10	7
Teachers who had never used Thymio	2	9	10
All teachers	7	19	17

Based on these methods, we created a survey of 63 questions that was submitted in digital form to the 180 participants in the teacher training sessions.

E. Respondents

The targeted group consisted of teachers who decided to take part in one or more training sessions involving Thymio. We received answers from 43 teachers (23.9%, almost one quarter of the original population), comprising 28 women and 15 men. Their average length of professional experience was 19.1 years (sd = 8.5). Table I shows the details of the age distribution. 22 had already used Thymio in their class, whereas 21 had not. The average professional experience of the participants was very similar in length between those who had already used Thymio in their class (≈ 20 years) and those who did not (≈ 18 years).

Concerning the topics they taught, 24 mentioned being generalist teachers (primary school), 13 specifically said they taught Mathematics and/or Physics, 9 mentioned Computer Science or Robotics, 2 mentioned Maturity Theses (end of high school projects). 3 said they were specialized teachers teaching only some topics, and 4 mentioned their role as Media & ICT responsibles[9]. All school levels (from kindergarten to high school) were represented in our sample.

This population tended to have a positive bias towards robotics and Thymio in particular, because they showed interest in the domain by subscribing to the training sessions, and because they gained knowledge and experience of using Thymio during these sessions. Due to this, we will not consider their motivation as representative of teachers in general, but rather as an indication of the perception and motivation of teachers who show an interest in the field. An understanding of their constraints and the obstacles they might face will help to develop better educational robots and materials.

[9] In Swiss primary schools, Media & ICT responsibles care for the use of media and technologies at their school. They coordinate resources and inform students and teachers about the use of media and technologies

III. RESULTS

A. Utility

What utility of the robot did the teachers perceive?

The teachers were asked to rate a certain number of affirmations on a four-points Likert scale (strongly disagree - disagree - agree - strongly agree). Concerning the utility, only 2 teachers disagreed with the statement "*According to you, Thymio allows pupils to acquire knowledge*", while 15 agreed and 26 strongly agreed. The 2 respondents who did not see any utility for the robot cited the young age of their pupils and the abundance of other available artifacts as reasons for their answer. Interestingly, the less enthusiastic answers (these 2 disagreements, and 9 of the 15 who agreed) were among the teachers who had already used Thymio.

Which school subjects are involved?

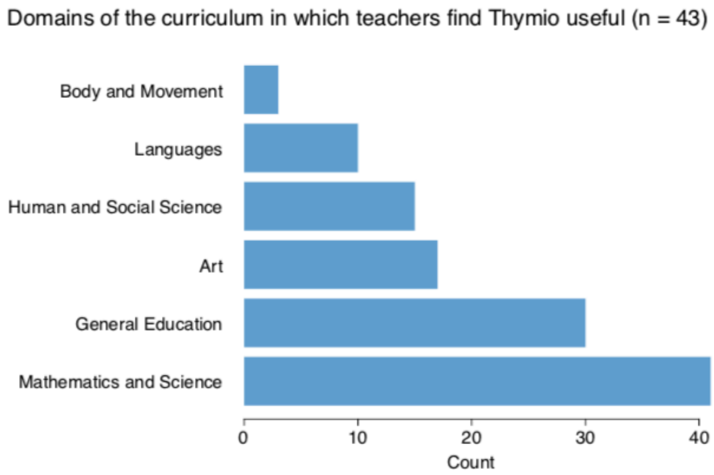
To characterize this utility, we asked teachers: "*According to you, in which domains of the PER[10] can Thymio be used?*" Nearly all agreed on "Mathematics and Sciences", and 30 also considered "General Education" to be a good fit. Other domains received less than half of the votes (see Fig. 3a). This corresponds with the participants' profiles regarding the topics they taught.

What kind of knowledge is targeted by teachers in the use of robots?

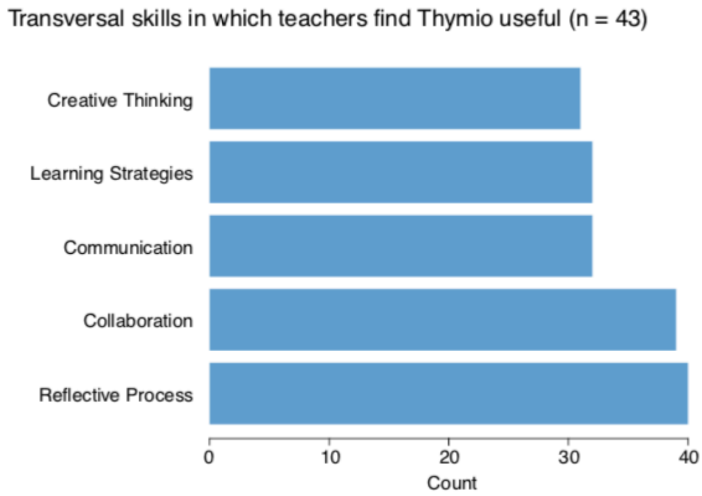
One respondent stated that "the goal is not to use Thymio in a specific domain [...] but to analyze clearly and precisely how Thymio adds value in the construction of certain knowledges." Indeed, it is interesting to understand teachers' objectives in robotic activities in the classroom. According to them, using Thymio allows them to target primarily transversal skills, especially the "reflective process" (93%) and "collaboration" (90%). Other transversal skills – "communication", "learning strategies", and "creative thinking" – also got an approval of over 70% (see Fig. 3b).

In addition, 65% of respondents agreed that "Thymio is a carrier of knowledge like any other" (15 strongly agreed, 13 agreed, 12 disagreed, and 3 strongly disagreed). The motivational aspect seems to be of great importance. 91% of respondents agreed that "Thymio enhances the pupils' commitment in the school's activities" (21 strongly agreed, 18 agreed, and 4 disagreed). One person noted, however, that "once the discovery phase is over, Thymio needs other qualities to stimulate commitment." This can be interpreted as a fear of the teachers or as a request to the designers. Although some anecdotical elements show that Thymio can be used for very long periods, additional data is needed to assess this. In any case, when asked if they would use Thymio as a pedagogical tool if it were available to them, only 2 out of 43 teachers said no, while all others agreed. Among their reasons, they mostly claimed that it is a good tool for applying the scientific thinking (making hypotheses, testing, drawing conclusions), that it helps to illustrate phenomena and to make abstract knowledge concrete, and that it is attractive for children, motivating, and fun. Some teachers also mentioned their interest in using various ways of teaching, and the richer interactions pupils have when working with robots.

[10] PER (Plan d'Etudes Romand) is the official Swiss French school curriculum.



(a) Domains of the Swiss curriculum (PER)



(b) Transversal objectives of the Swiss curriculum (PER)

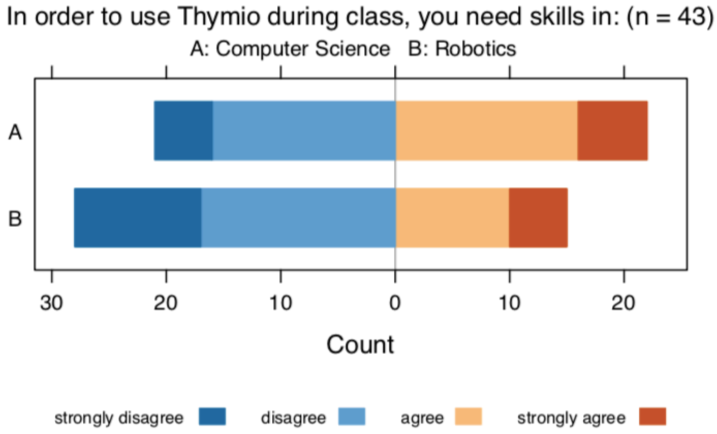
Fig. 3: Teachers' opinions on the disciplines in which Thymio is best suited.

B. Usability

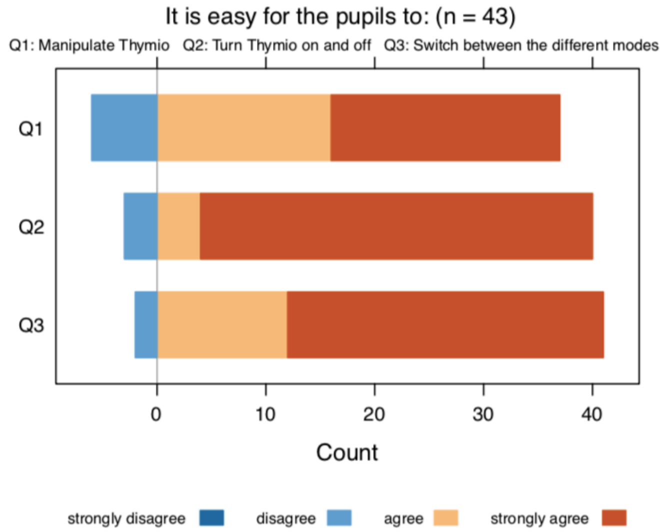
By usability, we refer to the evaluation of the possibility of using Thymio. We must take both sides into account: the teachers and the pupils' sides. Once again, these questions reflect the opinions of the teachers; analyzing these aspects will help us to understand what triggers or blocks the decision to use robots in class.

Which professional skills are required to use the device?

Concerning the question whether skills in computer science or robotics are needed for the use of Thymio during class, the teachers' opinions are fairly mixed (see Fig. 4a). The divide can especially be seen when it comes to computer science skills: half considered them necessary, while the other half did not. If we cross this data with the question "Have you used Thymio in your class before?", we see that the answers are correlated. People who have experience consider that computer science skills are not really necessary, while those who had never worked with Thymio thought they needed these types of skills (chi-squared test, p-value = 0.005). It could be that getting to know Thymio has reassured the users and shown them that they do not need advanced skills; or conversely, that the fear of lacking computer science skills had prevented some teachers from actually making use of the robot.



(a) Professional skills teachers consider necessary in order to use Thymio with their class.



(b) Teachers' opinions on Thymio's usability by pupils.

Fig. 4: Usability of Thymio.

What factors enable the use of robotics in class?

When asked "What allowed you to understand Thymio's functioning?", "What would have allowed you to more easily understand Thymio's functioning?", and "How could we improve Thymio's handling?", apart from answers focusing on technical improvements, many answers contained references to documentation ("more complete references on the programming language", "a wider tutorial", "better ASEBA documentation", "a guide with some well illustrated examples", "step-by-step videos"), including ready-to-use materials ("preprogrammed SD cards with different functions", "suggestions for ready-to-use programming activities", "a remote control (already programmed) sold with Thymio"), and to experience ("time spent interacting with it", "my attempts", "exercises like the children do", "for the basic programming the training session was sufficient, for more personalized programming, you need more knowledge", "I like to experiment with a good manual"). It would be interesting in further studies to evaluate how training and experience impact the use of robotics in class.

What is the perceived usability of the device? Can it be easily handled by the pupils?

When probed about the pupils' handling of Thymio, the answers were more confident (see Fig. 4b). Teachers mainly answered the question in the affirmative: it was easy for children to understand how to turn it on/off, or change mode.

Regarding the level of usability, it would seem that blocking occurs more on the level of the teachers' skills and confidence, rather than in the handling by children. This perception could change with wider use of Thymio. Indeed, the te**P**achers' experience would grow, making them more confident and skilled with the technology; at the same time, this would give them the opportunity to observe problems that arise during actual use of the device.

C. Acceptability

What is the perceived acceptability of integrating this type of device in teachers' practice?

To understand the robot's acceptability, we inquired about the teachers' motivations. A series of 18 questions allowed us to differentiate the various aspects in this regard.

The results show that the teachers' motivation was mainly intrinsic (see Fig. 5). In particular, the respondents showed a very strong intrinsic motivation for acquiring knowledge. This means that when using or intending to use Thymio in class, they aim to learn something new, even if it is not part of the curriculum. This intrinsic motivation is also characterized by its strong trend for fulfillment, underlying the fact that the teachers aim to be effective and competent in their professional practice when using Thymio. Finally, they were also intrinsically motivated by stimulation, i.e. the use of Thymio for its own sake, especially in the case of early adopters who had already used the robot.

The extrinsic motivation was mainly expressed by teachers who had never used Thymio. We observed 2 peaks of motivation; one through the teachers' identification of their own incentives, the other by external regulations.

The different type of motivation between experienced and inexperienced teachers is well illustrated by the statistically different answers to the following questions:

- "I use / want to use Thymio because I really love robots." Those who had used Thymio were more categorical about this than those who had just considered using it (chi-squared test, p-value = 0.002).
- "I use / want to use Thymio to present it at the parents' meeting day." Those who had used Thymio were mostly unmotivated by this, while the others found it more relevant (chi-squared test, p-value = 0.006).

What are the device's constraints in classroom use?

From the teachers' answers, we can gather some hints as to the obstacles they might encounter when trying to bring robots into the classroom. Several of them mentioned issues with the curriculum, namely that robots themselves are not mentioned and that it is hard to fit robotic activities into their practice.

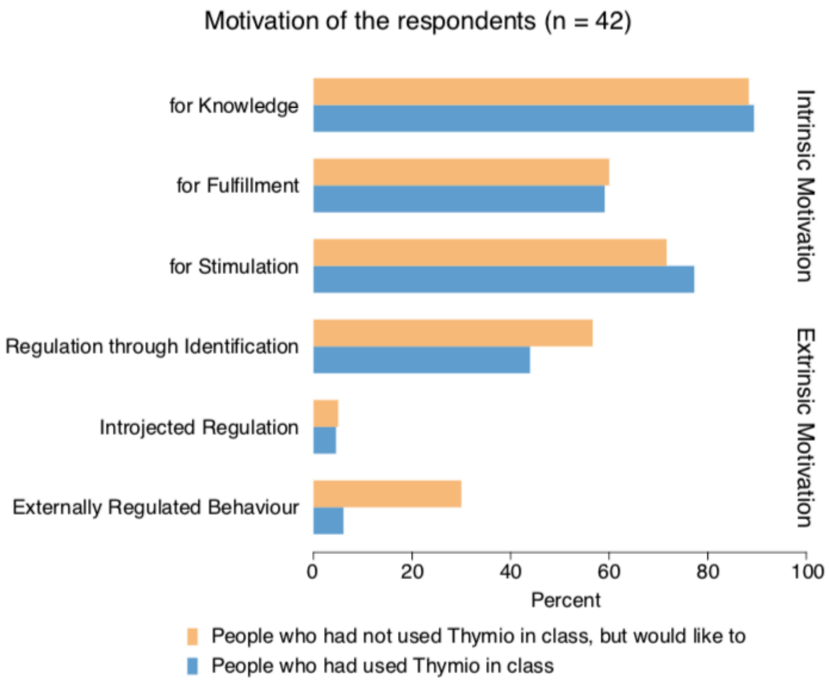


Fig. 5: Motivation of teachers: each type of motivation was measured by three different questions. Amotivation is not considered because this study covers only teachers who had decided to act, by attending at least one training session.

They also mentioned a lack of time in which to initiate robotics activities.

- "[I would use it] in high-school, for Mathematics and Physics, if there is time. In middle school (9-11 years old) it is not adapted: programming is too difficult and abstract, the behaviors are too simple and fixed."
- "I need to take time to find out how to use [the robots] in topics such as French or Math."
- "Outside of a Robotics course, I would use them very little, for a lack of time and ideas."
- "I have unfortunately not taken a lot of time to use them, because even as a Media & ICT responsible, there is still the curriculum's sword of Damocles threatening me."
- "In Maturity Theses, there is unfortunately not enough time. I would gladly use them in Technology or Math courses."
- "[I would use them], but obviously not in the prescribed school framework. Using Thymio regularly demands to rethink the learning process, to work in a different way, and, despite all, to prioritize the learning of scientific topics."

When asked whether they would receive the support of their superiors if they decided to use robots in class, most were confident: 35 said yes, 3 were unsure, and 4 said no. The acceptability of robots seems to depend more on the time needed to get acquainted with them and the adequacy with the curriculum than on the approval of the hierarchy.

In summary, the limits of acceptability are closely linked to the limits of usability. The fact that robots are not explicitly mentioned in the curriculum, and the time needed to gain experience and confidence, leads teachers to think that Thymio might not be directly adapted for class. Though the hierarchy is not presented as blocking factor, we sense a fear of not obtaining approval, or not fulfilling the program. We expect that with an improvement of usability (by providing more training opportunities, and pedagogical materials that are directly usable and have links with the curriculum), acceptability would also improve.

The weak weight of the extrinsic motivation shows the limited influence of the school on the practice of teachers concerning the use of robotics.

IV. CONCLUSIONS

The results of our survey confirm several findings of other studies, such as:

- the need for educational material, as seen in the analysis of the usability,
- the need for teacher training, as shown by the usability,
- the lack of institutional injunctions, mentioned as an obstacle in the acceptability feedbacks,
- the perceived utility of the robot by the teachers, clearly quantified in our study,
- the broad applicability of educational robotics, especially in the teaching of transversal skills.

Overall, we can confirm that Thymio has a high usability, at all school levels.

Our study allowed us to dig into more detailed mechanisms, based on the analysis of utility, usability, and acceptability, which are linked. The analysis of acceptability showed that the main motivation for teachers was intrinsic: first, they want to learn something new, want to be more professionally efficient, and they are interested in the device itself. External factors had less impact on their motivation, especially for the early adopters who were already using Thymio in their class. The rest of the teachers, who we can call “followers”, had a motivation that was based slightly more on external benefits or regulations, and we can expect this trend to grow in the future. It is also interesting to observe that the perceived utility of Thymio decreases when people use it in their class. This seems to show that the experience of using robots in real conditions brings up difficulties that a teacher does not foresee when looking at the device for the first time. However, the perceived utility is still high and well grounded. The study on usability also showed that teachers are more confident in the children’s ability to use the robot than their own. This underlines the importance of teacher training.

In our field, where most studies focus on the acceptability of robots by the pupils, we believe that it is extremely important to pay increased attention to the teachers, who play a key role in the use of robotics in education. We hope that the mechanisms highlighted by our study will help in defining better strategies for the deployment of robotics in schools, in particular by training the teachers and supporting them in their use of robotics tools.

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SUPPLEMENTARY MATERIAL

Questionnaire (French version)

CONCEPTS	VISEES	DIMENSIONS	QUESTIONS / INDICATEURS
Données sociologiques	pour situer la personne questionnée	formation suivie	1- Quelle(s) demi-journée(s) ou journée(s) de formation sur la robotique avez-vous suivie(s) en 2013 ?
		âge	25- Dans quelle tranche d'âge vous situez-vous ?
		sexe	26- De quel sexe êtes-vous ?
		expérience pro	27- Combien d'années d'expérience avez-vous en tant qu'enseignant ?
		spécialisation	28- Quelle(s) matière(s) enseignez-vous ?
		rapport hiérarchie	29- Estimez-vous avoir le soutien de votre direction concernant l'entreprise d'un projet de robotique dans votre classe ?
UTILITÉ	pour mesurer la conformité à la finalité du dispositif : est-ce que l'on fait réellement apprendre ce que l'on veut faire apprendre ? Qu'est-ce que le dispositif permet de faire vs ce que l'utilisateur veut en faire (catachrèse vs affordance)	adéquation entre objectif défini et apprentissage effectif	5- Selon vous, Thymio II permet aux élèves de réaliser des apprentissages.
			6- Selon vous, dans quel(s) domaine(s) du PER pouvez-vous utiliser Thymio II ?
			7- Selon vous, en visant quel(s) objectifs transversaux du PER pouvez-vous utiliser Thymio II ?
			13- Il est possible d'ajouter des "Légo" classiques sur Thymio II, des "Légo Technic" sur ses roues, de construire une poulie avec le mouvement de la roue… Pensez-vous que ces fonctionnalités sont intéressantes pour les apprentissages de vos élèves ? [Légo classique]
			13- Il est possible d'ajouter des "Légo" classiques sur Thymio II, des "Légo Technic" sur ses roues, de construire une poulie avec le mouvement de la roue… Pensez-vous que ces fonctionnalités sont intéressantes pour les apprentissages de vos élèves ? [Légo Technic]
			13- Il est possible d'ajouter des "Légo" classiques sur Thymio II, des "Légo Technic" sur ses roues, de construire une poulie avec le mouvement de la roue… Pensez-vous que ces fonctionnalités sont intéressantes pour les apprentissages de vos élèves ? [Mouvement de la roue]
			13- Il est possible d'ajouter des "Légo" classiques sur Thymio II, des "Légo Technic" sur ses roues, de construire une poulie avec le mouvement de la roue… Pensez-vous que ces fonctionnalités sont intéressantes pour les apprentissages de vos élèves ? [Un crayon feutre dans le trou pour réaliser des tracer]
			14a- Si vous avez répondu "oui", indiquez vos raisons.
			14b- Si vous avez répondu "non", indiquez vos raisons.
			19- Selon vous, Thymio II stimule l'engagement des élèves dans les activités scolaires.
			20- Si vous aviez des Thymio II à disposition, les utiliseriez-vous comme outil pédagogique ?
			21- Pour quelle(s) raison(s) ?

		Préférences	22- Si vous aviez à disposition tous les outils cités ci-après, dans quel ordre de préférence les utiliseriez-vous ? [Thymio II] 22- Si vous aviez à disposition tous les outils cités ci-après, dans quel ordre de préférence les utiliseriez-vous ? [Légo Mindstorm] 22- Si vous aviez à disposition tous les outils cités ci-après, dans quel ordre de préférence les utiliseriez-vous ? [Légo WeDo] 22- Si vous aviez à disposition tous les outils cités ci-après, dans quel ordre de préférence les utiliseriez-vous ? [Beebot] 22- Si vous aviez à disposition tous les outils cités ci-après, dans quel ordre de préférence les utiliseriez-vous ? [Ordinateur] 22- Si vous aviez à disposition tous les outils cités ci-après, dans quel ordre de préférence les utiliseriez-vous ? [Tablette tactile]
UTILISABILITÉ	pour mesurer la maniabilité du dispositif, c'est-à-dire les possibilités de manipuler,de mettre en œuvre	prérequis	8- Selon vous, pour utiliser Thymio II en classe il faut avoir des compétences en informatique. 9- Selon vous, pour utiliser Thymio II en classe il faut avoir des compétences en robotique.
		statut instrument	10- Selon vous, Thymio II est un vecteur comme un autre pour transmettre un savoir.
		maniabilité	11- Selon vous, Thymio II est maniable facilement par vos élèves.
	le dispositif : est-ce que le dispositif est aisément manipulable par les apprenants ?		12- Selon vous, il est facile de comprendre comment allumer / éteindre Thymio II. 15- Selon vous, il est facile de comprendre comment activer les modes de Thymio II. 16- Qu'est-ce qui vous a permis de comprendre le fonctionnement de Thymio II ? 17- Qu'est-ce qui vous aurait permis de comprendre plus aisément le fonctionnement de Thymio II ? 18- Selon vous, comment pourrait-on améliorer la maniabilité de Thymio II ?
		valeurs liées à la pratique de l'enseignant	2- Pourquoi vous étiez-vous inscrit à une ou plusieurs de ces formations sur la robotique ? 3- Est-ce que la ou les formations que vous avez suivie(s) ont répondu à vos attentes ? 4- Pour quelle(s) raison(s) ?
		motivation (intrinsèque et extrinsèque)	23- Avez-vous déjà utilisé Thymio II en classe ?
		Motivation extrinsèque - régulation externe	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que mes collègues l'utilisent déjà.]
		Motivation intrinsèque à la connaissance	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que j'éprouve du plaisir et de la satisfaction à enseigner de nouvelles choses.]
		Motivation extrinsèque - identifiée	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce qu'utiliser Thymio II m'a aidé à réaliser une partie du programme de sciences.]
		Motivation intrinsèque à la stimulation	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que j'aime vraiment la robotique.]
	pour mesurer les possibilités d'accéder et de prendre la décision d'utiliser le dispositif, d'être motivé pour utiliser celui-ci, de persister à l'utiliser même si des difficultés se	Motivation intrinsèque à l'accomplissement	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Pour le plaisir que je ressens à me surpasser quand j'utilise un nouvel objet technique.]
		Motivation extrinsèque - introjectée	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Pour me prouver à moi-même que je suis capable de faire autant que des collègues qui utilisent des robots.]
		Motivation extrinsèque - régulation externe	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Pour pouvoir présenter ce projet à la réunion de parents.]
		Motivation intrinsèque à la connaissance	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Pour le plaisir que j'ai à enseigner des choses jamais vues auparavant.]

ACCEPTABILITÉ	présentent : est-ce que le dispositif est compatible avec les pratiques, les ressources, les contraintes, les objectifs des usagers potentiels et de leur situation de travail ? Quelle est l'intention d'usage suscitée par le dispositif ?	Motivation intrinsèque à la stimulation	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que pour moi la robotique c'est stimulant.]
		Motivation intrinsèque à l'accomplissement	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Pour le plaisir que je ressens lorsque je suis en train de me surpasser dans une de mes réalisations personnelles.]
		Motivation extrinsèque - introjectée	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce qu'utiliser Thymio II fait que mes élèves m'apprécient davantage.]
		Motivation extrinsèque - identifiée	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que cela m'a aidé à mieux choisir mon prochain programme d'activités en sciences.]
		Motivation intrinsèque à la stimulation	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que j'aime me sentir enthousiasmé(e) quand je montre à mes élèves un nouvel objet.]
		Motivation extrinsèque - régulation externe	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Pour proposer un atelier robotique sur le temps de midi.]
		Motivation intrinsèque à la connaissance	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce qu'avec Thymio II, je fais appel à des connaissances qui m'intéressent.]
		Motivation extrinsèque - identifiée	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce qu'utiliser Thymio II me permet d'améliorer mes compétences dans le domaine des sciences.]
		Motivation intrinsèque à l'accomplissement	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que faire de la robotique me permet d'améliorer mes compétences personnelles.]
		Motivation extrinsèque - introjectée	24a- Pourquoi avez-vous utilisé Thymio II en classe ? [Parce que si mes collègues utilisent Thymio II et moi pas, alors j'ai l'impression d'être un-e moins bon-ne enseignant-e.]
		formulation conditionnelle	23bis- Aimeriez-vous pouvoir utiliser Thymio II en classe ?
		Motivation extrinsèque - régulation externe	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que mes collègues l'utiliseraient déjà.]
		Motivation intrinsèque à la connaissance	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que j'éprouverais du plaisir et de la satisfaction à enseigner de nouvelles choses.]
		Motivation extrinsèque - identifiée	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce qu'utiliser Thymio II m'aiderait à réaliser une partie du programme de sciences.]
		Motivation intrinsèque à la stimulation	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que j'aime vraiment la robotique.]
		Motivation intrinsèque à l'accomplissement	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Pour le plaisir que je ressentirais à me surpasser en utilisant un nouvel objet technique.]
		Motivation extrinsèque - introjectée	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Pour me prouver à moi-même que je pourrais être capable de faire autant que des collègues qui utiliseraient déjà des robots.]
		Motivation extrinsèque - régulation externe	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Pour pouvoir présenter ce projet à une réunion de parents.]
		Motivation intrinsèque à la connaissance	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Pour le plaisir que j'aurais à enseigner des choses jamais vues auparavant.]
		Motivation intrinsèque à la stimulation	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que pour moi la robotique c'est stimulant.]
		Motivation intrinsèque à l'accomplissement	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Pour le plaisir que je pourrais ressentir en me surpassant dans une de mes réalisations personnelles.]
		Motivation extrinsèque - introjectée	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce qu'utiliser Thymio II ferait que mes élèves m'apprécieraient davantage.]
		Motivation extrinsèque - identifiée	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que cela pourrait m'aider à mieux choisir mon prochain programme d'activités en sciences.]

		Motivation intrinsèque à la stimulation	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que j'aime me sentir enthousiasmé(e) quand je montre à mes élèves un nouvel objet.]
		Motivation extrinsèque - régulation externe	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Pour proposer un atelier robotique sur le temps de midi.]
		Motivation intrinsèque à la connaissance	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce qu'avec Thymio II, je ferais appel à des connaissances qui m'intéressent.]
		Motivation extrinsèque - identifiée	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce qu'utiliser Thymio II me permettrait d'améliorer mes compétences dans le domaine des sciences.]
		Motivation intrinsèque à l'accomplissement	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que faire de la robotique me permettrait d'améliorer mes compétences personnelles.]
		Motivation extrinsèque - introjectée	24b- Pourquoi utiliseriez-vous Thymio II en classe ? [Parce que si mes collègues utilisaient Thymio II et moi pas, alors j'aurais l'impression d'être un-e moins bon-ne enseignant-e.]

Questionnaire (English version)

CONCEPTS	GOALS	DIMENSIONS	QUESTIONS / INDICATORS
Sociological data	to situate the person being questioned	training followed	1- Which half-day(s) or day(s) of training on robotics did you attend in 2013?
		age	25- In which age group are you?
		gender	26- What is your gender?
		professional experience	27- How many years of experience do you have as a teacher?
		specialisation	28- What subject(s) do you teach?
		hierarchy report	29- Do you feel that you have the support of your principal to undertake a robotics project in your class?
UTILITY	to measure compliance with the purpose of the device: does it really teach what it is intended to teach? What does the device allow to be done vs. what the user wants to do with it (catachresis vs. affordance)	match between defined objective and actual learning	5- According to you, Thymio II allows students to achieve learning.
			6- According to you, in which domain(s) of the PER can you use Thymio II?
			7- According to you, in which transversal objectives of the PER can you use Thymio II?
			13- It is possible to add classic "Lego" on Thymio II, "Lego Technic" on its wheels, to build a pulley with the movement of the wheel... Do you think that these functionalities are interesting for the learning of your pupils? [Classic Lego]
			13- It is possible to add classic "Légo" on Thymio II, "Légo Technic" on its wheels, to build a pulley with the movement of the wheel... Do you think that these functionalities are interesting for the learning of your students? [Lego Technic]
			13- It is possible to add classic "Légo" on Thymio II, "Légo Technic" on its wheels, to build a pulley with the movement of the wheel... Do you think that these functionalities are interesting for the learning of your students? [Wheel movement].
			13- It is possible to add classic "Lego" on Thymio II, "Lego Technic" on its wheels, to build a pulley with the movement of the wheel... Do you think that these functionalities are interesting for the learning of your students? [A felt-tip pen in the hole to make drawings]
			14a- If you answered "yes", give your reasons.
			14b- If you answered "no", please give your reasons.
			19- According to you, Thymio II stimulates students' engagement in school activities.
			20- If you had Thymio IIs at your disposal, would you use them as a teaching tool?
			21- For what reason(s)?
		preferences	22- If you had all the tools listed below at your disposal, in what order of preference would you use them? [Thymio II]
			22- If you had all the tools listed below at your disposal, in what order of preference would you use them? [Lego Mindstorm].
			22- If you had all the tools listed below at your disposal, in which order would you prefer to use them? [Lego WeDo].
			22- If you had all the tools listed below at your disposal, in which order would you prefer to use them? [Beebot].
			22- If you had all the tools listed below at your disposal, in what order would you prefer to use them? [Computer].
			22- If you had all the tools listed below at your disposal, in what order of preference would you use them? [Touch tablet]

USABILITY	to measure the manageability of the device, i.e. the possibilities of manipulating, implementing the device: is the device easily manipulated by the learners?	prerequisites	8- According to you, to use Thymio II in class you need to have computer skills. 9- According to you, to use Thymio II in class you need to have robotics skills.
		instrument status	10- According to you, Thymio II is a vehicle like any other to transmit knowledge.
		handling	11- According to you, Thymio II is easy to handle by your students. 12- According to you, it is easy to understand how to turn Thymio II on and off. 15- According to you, it is easy to understand how to activate the modes of Thymio II. 16- What allowed you to understand how Thymio II works? 17- What would have allowed you to understand more easily the functioning of Thymio II? 18- In your opinion, how could the handling of Thymio II be improved?
ACCEPTABILITY	to measure the possibilities of accessing and deciding to use the device, of being motivated to use it, of persisting in using it even if difficulties arise: is the device compatible with the practices, resources, constraints, objectives of the potential users and their work situation? What is the intention to use the device?	values related to the teacher's practice	2- Why did you register for one or more of these robotics training courses? 3- Did the training course(s) you attended meet your expectations? 4- For what reason(s)?
		motivation (intrinsic and extrinsic)	23- Have you ever used Thymio II in class?
		Extrinsic motivation - external regulation	24a- Why did you use Thymio II in class? [Because my colleagues already use it].
		Intrinsic motivation to know	24a- Why did you use Thymio II in class? [Because I get pleasure and satisfaction from teaching new things].
		Extrinsic motivation - identified	24a- Why did you use Thymio II in the classroom? [Because using Thymio II has helped me to complete part of the science curriculum].
		Intrinsic motivation to stimulate	24a- Why did you use Thymio II in class? [Because I really like robotics].
		Intrinsic motivation to achieve	24a- Why did you use Thymio II in class? [For the fun I have in challenging myself when I use a new technical object].
		Extrinsic motivation - introjected	24a- Why did you use Thymio II in class? [To prove to myself that I am capable of doing as much as my colleagues who use robots].
		Extrinsic motivation - external regulation	24a- Why did you use Thymio II in class? [To be able to present this project at the parents' meeting].
		Intrinsic motivation to know	24a- Why did you use Thymio II in class? [For the fun I have teaching things I have never seen before].
		Intrinsic motivation to stimulate	24a- Why did you use Thymio II in class? [Because robotics is stimulating for me].
		Intrinsic motivation to achieve	24a- Why did you use Thymio II in class? [For the fun I get when I'm outdoing myself in one of my personal achievements].
		Extrinsic motivation - introjected	24a- Why did you use Thymio II in class? [Because using Thymio II makes my students like me more].

		Extrinsic motivation - identified	24a- Why did you use Thymio II in class? [Because it helped me to better choose my next science curriculum].
		Intrinsic motivation to stimulate	24a- Why did you use Thymio II in class? [Because I like to feel excited when I show my students a new object].
		Extrinsic motivation - external regulation	24a- Why did you use Thymio II in class? [To offer a robotics workshop at lunchtime].
		Intrinsic motivation to know	24a- Why did you use Thymio II in class? [Because with Thymio II, I use knowledge that interests me].
		Extrinsic motivation - identified	24a- Why did you use Thymio II in class? [Because using Thymio II allows me to improve my science skills].
		Intrinsic motivation to achieve	24a- Why did you use Thymio II in class? [Because doing robotics helps me improve my personal skills].
		Extrinsic motivation - introjected	24a- Why did you use Thymio II in class? [Because if my colleagues use Thymio II and I don't, then I feel like I'm not as good a teacher].
		Conditional formulation	23bis- Would you like to use Thymio II in class?
		Extrinsic motivation - external regulation	24b- Why would you use Thymio II in class? [Because my colleagues would already use it].
		Intrinsic motivation to know	24b- Why would you use Thymio II in class? [Because I would enjoy and get satisfaction from teaching new things].
		Extrinsic motivation - identified	24b- Why would you use Thymio II in the classroom? [Because using Thymio II would help me to complete part of the science curriculum].
		Intrinsic motivation to stimulate	24b- Why would you use Thymio II in class? [Because I really like robotics].
		Intrinsic motivation to achieve	24b- Why would you use Thymio II in class? [For the fun I would have in challenging myself with a new technical object].
		Extrinsic motivation - introjected	24b- Why would you use Thymio II in class? [To prove to myself that I might be able to do as much as colleagues who are already using robots].
		Extrinsic motivation - external regulation	24b- Why would you use Thymio II in class? [To be able to present this project at a parents' meeting].
		Intrinsic motivation to know	24b- Why would you use Thymio II in class? [For the fun I would have teaching things I have never seen before].
		Intrinsic motivation to stimulate	24b- Why would you use Thymio II in class? [Because robotics is stimulating for me].
		Intrinsic motivation to achieve	24b- Why would you use Thymio II in class? [For the pleasure I could get from surpassing myself in one of my personal achievements].
		Extrinsic motivation - introjected	24b- Why would you use Thymio II in class? [Because using Thymio II would make my students like me more].

		Extrinsic motivation - identified	24b- Why would you use Thymio II in class? [Because it might help me choose my next science curriculum better].
		Intrinsic motivation to stimulate	24b- Why would you use Thymio II in class? [Because I like to feel excited when I show my students a new object].
		Extrinsic motivation - external regulation	24b- Why would you use Thymio II in class? [To offer a robotics workshop at lunchtime].
		Intrinsic motivation to know	24b- Why would you use Thymio II in class? [Because with Thymio II, I would use knowledge that interests me].
		Extrinsic motivation - identified	24b- Why would you use Thymio II in class? [Because using Thymio II would help me improve my science skills].
		Intrinsic motivation to achieve	24b- Why would you use Thymio II in class? [Because doing robotics would improve my personal skills].
		Extrinsic motivation - introjected	24b- Why would you use Thymio II in class? [Because if my colleagues used Thymio II and I didn't, then I would feel like a lesser teacher].

Paper #2

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Fostering computational thinking through educational robotics: a model for creative computational problem solving

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Abstract

Background: Educational robotics (ER) is increasingly used in classrooms to implement activities aimed at fostering the development of students' computational thinking (CT) skills. Though previous works have proposed different models and frameworks to describe the underlying concepts of CT, very few have discussed how ER activities should be implemented in classrooms to effectively foster CT skill development. Particularly, there is a lack of operational frameworks, supporting teachers in the design, implementation, and assessment of ER activities aimed at CT skill development. The current study therefore presents a model that allows teachers to identify relevant CT concepts for different phases of ER activities and aims at helping them to appropriately plan instructional interventions. As an experimental validation, the proposed model was used to design and analyze an ER activity aimed at overcoming a problem that is often observed in classrooms: the trial-and-error loop, i.e., an over-investment in programming with respect to other tasks related to problem-solving.

Results: Two groups of primary school students participated in an ER activity using the educational robot Thymio. While one group completed the task without any imposed constraints, the other was subjected to an instructional intervention developed based on the proposed model. The results suggest that (i) a non-instructional approach for educational robotics activities (i.e., unlimited access to the programming interface) promotes a trial-and-error behavior; (ii) a scheduled blocking of the programming interface fosters cognitive processes related to problem understanding, idea generation, and solution formulation; (iii) progressively adjusting the blocking of the programming interface can help students in building a well-settled strategy to approach educational robotics problems and may represent an effective way to provide scaffolding.

Conclusions: The findings of this study provide initial evidence on the need for specific instructional interventions on ER activities, illustrating how teachers could use the proposed model to design ER activities aimed at CT skill development. However, future work should investigate whether teachers can effectively take advantage of the model for their teaching activities. Moreover, other intervention hypotheses have to be explored and tested in order to demonstrate a broader validity of the model.

Keywords: Computational thinking, Educational robotics, Instructional intervention, Problem solving, Trial-and-error

Introduction

Educational robotics (ER) activities are becoming increasingly popular in classrooms. Among others, ER activities have been praised for the development of important twenty-first century skills such as creativity (Eguchi, 2014; Negrini & Giang, 2019; Romero, Lepage, & Lille, 2017) and collaboration (Denis & Hubert, 2001; Giang et al., 2019). Due to its increasing popularity, ER is also often used to implement activities aimed at fostering CT skills of students. Such activities usually require students to practice their abilities in problem decomposition, abstraction, algorithm design, debugging, iteration, and generalization, representing six main facets of CT (Shute, Sun, & Asbell-Clarke, 2017). Indeed, previous works have argued that ER can be considered an appropriate tool for the development of CT skills (Bers, Flannery, Kazakoff, & Sullivan, 2014; Bottino & Chioccariello, 2014; Catlin & Woollard, 2014; Chalmers, 2018; Eguchi, 2016; Leonard et al., 2016; Miller & Nourbakhsh, 2016).

Nevertheless, studies discussing how to implement ER activities for CT skills development in classrooms, still appear to be scarce. The latest meta-analyses carried out on ER and CT (Hsu, Chang, & Hung, 2018; Jung & Won, 2018; Shute et al., 2017) have mentioned only four works between 2006 and 2018 that elaborated how ER activities should be implemented in order to foster CT skills in K-5 education (particularly for grades 3 and 4, i.e., for students of age between 8 and 10 years old). Another recent work (Ioannou & Makridou, 2018) has shown that there are currently only nine empirical investigations at the intersection of ER and CT in K-12. Among the recommendations for researchers that were presented in this work, the authors stated that it is important to "work on a practical framework for the development of CT through robotics." A different study (Atmatzidou & Demetriadis, 2016) has pointed out that there is a lack of "explicit teacher guidance on how to organize a well-guided ER activity to promote students' CT skills."

In the meta-analysis of Shute et al. (2017), the authors reviewed the state of the art of existing CT models and concluded that the existing models were inconsistent, causing "problems in designing interventions to support CT learning." They therefore synthesized the information and proposed a new CT model represented by the six main facets mentioned above (Shute et al., 2017). Though the authors suggested that this model may provide a framework to guide assessment and support of CT skills, the question remains whether teachers can take advantage of such models and put them into practice. In order to support teachers in the design, implementation, and assessment of activities addressing these CT components, it can be presumed that more operational frameworks are needed. Particularly, such frameworks should provide ways to identify specific levers that teachers can adjust to promote the development of CT skills of students in ER activities.

To address this issue, the present work aims at providing an operational framework for ER activities taking into consideration two main aspects of CT, computation, and creativity, embedded in the context of problem-solving situations. The objective of the present study is to obtain a framework that allows teachers to effectively design ER activities for CT development, anticipate what could occur in class during the activities, and accordingly plan specific interventions. Moreover, such framework could potentially allow teachers to assess the activities in terms of CT competencies developed by the students.

To verify the usefulness of the proposed framework, it has been used to design and analyze an ER activity aimed at overcoming a situation that is often observed in classrooms: the trial-and-error loop. It represents an over-investment in programming with respect to other problem-solving tasks during ER activities. In the current study, an ER activity has been developed and proposed to two groups of primary school pupils: a test group and a control group, each performing the same task under different experimental conditions. The students were recorded during the activity and the videos have been analyzed by two independent evaluators to study the effectiveness of instructional interventions designed according to the proposed framework and implemented in the experimental condition for the test groups.

In the following section, past works at the intersection of ER and CT are summarized. This is followed by the presentation of the creative computational problem-solving (CCPS) model for ER activities aimed at CT skills development. Subsequently, the research questions addressed in this study are described, as well as the methods for the experimental validation of this study. This is followed by the presentation of the experimental results and a discussion on these findings. The paper finally concludes with a summary on the possible implications and the limitations of the study.

Background

What three meta-analyses at the crossroads of ER and CT have shown.

The idea of using robots in classrooms has a long history — indeed, much time has passed since the idea was first promoted by Papert in the late 1970s (Papert, 1980). On the other hand, the use of ER to foster CT skills development appears to be more recent — it was in 2006 that Jeannette Wing introduced the expression "computational thinking" to the educational context (Wing, 2006). It is therefore not surprising that only three meta-analyses have examined the studies conducted on this topic between 2006 and 2017 (Hsu et al., 2018; Jung & Won, 2018; Shute et al., 2017).

In the first meta-analysis (Jung & Won, 2018), Jung and Won describe a systematic and thematic review on existing ER literature (n = 47) for K-5 education. However, only four out of the 47 analyzed articles related ER to CT and only two of them (Bers et al., 2014; Sullivan, Bers, & Mihm, 2017) conveyed specific information about how to teach and learn CT, yet limited to K-2 education (with the Kibo robot and the TangibleK platform).

In a second meta-analysis (Hsu et al., 2018), Hsu et al. conducted a meta-review on CT in academic journals (n = 120). As a main result, the authors concluded that "CT has mainly been applied to activities of program design and computer science." This focus on programming seems to be common and has been questioned before — among others, it has been argued that CT competencies consist of more than just skills related to programming.

A similar conclusion was found in the third meta-analysis (Shute et al., 2017). Shute et al. conducted a review among literature on CT in K-16 education (n = 45) and stated that "considering CT as knowing how to program may be too limiting." Nevertheless, the relation between programming and CT seems to be interlinked. The authors suggested that "CT skills are not the same as programming skills (Ioannidou, Bennett, Repenning, Koh, & Basawapatna, 2011), but being able to program is one benefit of being able to think computationally (Israel, Pearson, Tapia, Wherfel, & Reese, 2015)."

According to the findings of these three recent meta-analyses, it appears that there is still a lack of studies focusing on how ER can be used for CT skills development. Except for two studies that specifically describe how to teach and learn CT with ER in K-2 education, operational frameworks guiding the implementation of ER activities for students, especially those aged between 8 and 10 years old (i.e., grades 3 and 4), are still scarce. It also emerges that in the past, activities aimed at CT development have focused too much on the programming aspects. However, CT competences go beyond the limitations on pure coding skills and ER activities should therefore be designed accordingly.

CT development with ER is more than just programming a robot.

Because robots can be programmed, ER has often been considered a relevant medium for CT skill development. However, many researchers have also argued that CT is not only programming. As illustrated by Li et al. (2020), CT should be considered "as a model of thinking that is more about thinking than computing" (p.4). In the work of Bottino and Chioccariello (2014), the authors are reminiscent of what Papert claimed about the use of robots (Papert, 1980). Programming concrete objects such as robots support students' active learning as robots can "provide immediate feedback and concept reification." The programming activity is thus not the only one that is important for CT skills development. Instead, evaluating (i.e., testing and observing) can be considered equally important. In the 5c21 framework for CT competency of Romero et al. (2017), both activities therefore represent separate components: create a computer program (COMP5) and evaluation and iterative improvement (COMP6).

While the evaluation of a solution after programming appears to be natural for most ER activities, it seems that activities prior to programming often receive far less attention. Indeed, it is also relevant to explore what activities are required before programming, that is to say, before translating an algorithm into a programming language for execution by a robot. Several efforts have shown that different activities can be carried out before the programming activity (Giannakoulas & Xinogalos, 2018; Kazimoglu, Kiernan, Bacon, & MacKinnon, 2011, 2012). For instance, puzzle games such as Lightbot (Yaroslavski, 2014) can be used to convey basic concepts needed before programming (Giannakoulas & Xinogalos, 2018). In another work (Kazimoglu et al., 2012), a fine effort has been made to put in parallel the task to be done by the student (with a virtual bot) and the cognitive activity implied. This is how the authors sustained the CT skills of students before programming. The integration of such instructional initiatives prior to programming is usually aimed at introducing fundamental concepts necessary for the programming activities. Indeed, code literacy (COMP3) and technological system literacy (COMP4) have been described as two other components in the framework of Romero et al. (2017), and they have been considered important prerequisites for the use of programmable objects.

But even if students meet these prerequisites, there are other important processes that they should go through prior to the creation of executable code. The two following components in the framework of Romero et al. are related to these processes: problem identification (COMP1) and organize and model the situation (COMP2). However, it appears that in the design of ER activities, these aspects are often not given enough attention. In a classroom environment, robots and computers often attract students' attention to such an extent that the students tend to dive into a simple trial-and-error approach instead of developing proper solution strategies. Due to the prompt feedback of the machine, students receive an immediate validation of their strategy, reinforcing their perception of controllability (Viau, 2009), but this also causes them to easily enter in a trial-and-error loop (Shute et al., 2017). In many different learning situations, however, researchers have shown that a pure trial-and-error-approach may limit skill development (Antle, 2013; Sadik, Leftwich, & Nadiruzzaman, 2017; Tsai, Hsu, & Tsai, 2012). In the context of inquiry-based science learning, Bumbacher et al. have shown that students who were instructed to follow a Predict-Observe-Explain (POE) strategy, forcing them to take breaks between actions, gained better conceptual understanding than students who used the same manipulative environment without any instructions (Bumbacher, Salehi, Wieman, & Blikstein, 2018). The strategic use of pauses has also been investigated by Perez et al. (2017) in the context of students who worked with a virtual lab representing a DC circuit construction kit. The authors argued that strategic pauses can represent opportunities for reflection and planning and are highly associated with productive learning. A similar approach has been discussed by Dillenbourg (2013) who introduced a paper token to a tangible platform to prevent students from running simulations without reflection. Only when students gave a satisfactory answer to the teacher about the predicted behavior of the platform, they were given the paper token to execute the simulations.

However, to this day such instructional interventions have not been applied to activities involving ER. As a matter of fact, many ER activities are conducted without any specific instructional guidance. As elaborated before, the development of CT skills with ER should involve students in different phases that occur prior as well as after the creation of programming code. While most of the time, the evaluation of a solution after programming appears to be natural, the phases required prior to programming are usually less emphasized. These preceding phases, however, incorporate processes related to many important facets of CT and should therefore be equally addressed. The following section therefore introduces a model for ER activities that allows teachers to identify all relevant phases related to different CT skills. Based on this model, teachers may accordingly plan instructional interventions to foster the development of such CT skills.

The CCPS model

Educational robotic systems for the development of CT skills.

Educational robotics activities are typically based on three main components: one or more educational robots, an interaction interface allowing the user to communicate with the robot and one or more tasks to be solved on a playground (Fig. 1).

This set of components is fundamental to any kind of ER activity and has been previously referred to as an Educational Robotics System (ERS) by Giang, Piatti, and Mondada (2019). When an ERS is used for the development of CT skills, the given tasks are often formulated as open-ended problems that need to be solved. These problems are usually statements requiring the modification of a given perceptual reality (virtual or concrete) through a creative act in order to satisfy a set of conditions.

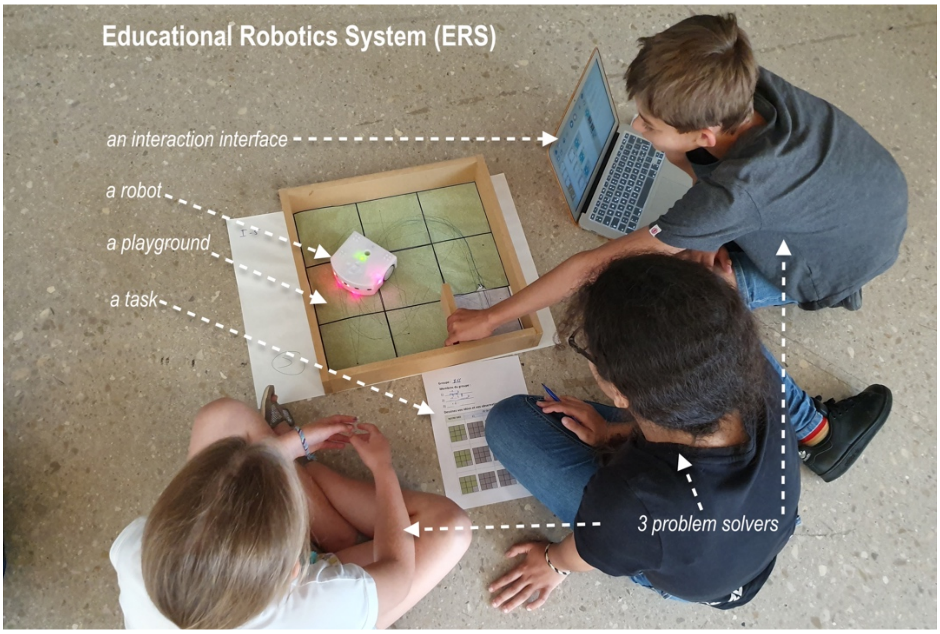

Fig.1 Example of an educational robotics (ER) activity. The figure exemplifies a typical situation encountered in ER activities. One or more problem solvers work on a playground and confront a problem situation involving an Educational Robotics System (ERS), consisting of one or more robots, an interaction interface and one or more tasks to be solved.

In most cases, a playground relates to the environment (offering the range of possibilities) in which the problem is embedded. The modification can consist in the creation of a new entity or the realization of an event inside the playground, respectively, the acquisition of new knowledge about the playground itself. A modification that satisfies the conditions of the problem is called solution. The problem solver is a human (or a group of humans), that is able to understand and interpret the given problem, to create ideas for its resolution, to use the interaction interface to transform these ideas into a behavior executed by the robot, and to evaluate the solution represented by the behavior of the robot. The language of the problem solver and the language of the robot are usually different. While the (human) problem solver's language consists of natural languages (both oral and written), graphical, or iconic representations and other perceptual semiotic registers, the (artificial) language of the robot consists of formal languages (i.e., machine languages, binary code). Consequently, the problem should be stated in the problem solver's language, while the solution has to be implemented in the robot's language. For the problem solver, the robot's language is a sort of foreign language that he/she should know in order to communicate with the robot. On the other hand, the robot usually does not communicate directly with the problem solver but generates a modification of the playground that the problem solver can perceive through his/her senses. To facilitate the interaction, the robot embeds a sort of translator between the robot's language and the problem solver's language. Indeed, graphical or text programming languages allow part of the language of the robot to be shown and written in iconic representations that can be directly perceived by the problem solver.

Combining creative problem solving and computational problem solving.

It has often been claimed that CT is a competence related to the process of problem solving that is contextualized in "computational" situations (Barr & Stephenson, 2011; Dierbach, 2012; Haseski, Ilic, & Tugtekin, 2018; Perkovic, Settle, Hwang, & Jones, 2010; Weintrop et al., 2016). These processes involve in particular the understanding of a given problem situation, the design of a solution, and the implementation in executable code. At the same time, some researchers have pointed out that the development of CT competencies also involves a certain creative act (Brennan & Resnick, 2012; DeSchryver & Yadav, 2015; Repenning et al., 2015; Romero et al., 2017; Shute et al., 2017). This perspective refers to creative problem solving which involves "a series of distinct mental operations such as collecting information, defining problems, generating ideas, developing solutions, and taking action" (Puccio, 1999). In a different context, creative problem solving has been described as a cooperative iterative process (Lumsdaine & Lumsdaine, 1994) involving different persons with different mindsets and thinking modes and consisting of five phases: problem definition (detective and explorer), idea generation (artist), idea synthesis (engineer), idea evaluation (judge), and solution implementation (producer) (Lumsdaine & Lumsdaine, 1994).

The creative computational problem solving (CCPS) model presented in the current study, represents a hybrid model combining these two perspectives and adapting them to the context of ERS. Similar to the model of Lumsdaine and Lumsdaine (1994), the proposed model involves the definition of different phases and iterations. However, while Lumsdaine and Lumsdaine's model describes the interactions between different human actors, each taking a specific role in the problem-solving process, this model considers the fact that different human actors interact with one or more artificial actors, i.e., the robot(s), to implement the solution. The CCPS model is a structure of five phases, in which transitions are possible, in each moment, from any phase to any other (Fig. 2).

The first three phases of the model can be related to the initial phases of the creative problem-solving model presented in the work of Puccio (1999): understanding the problem, generating ideas, and planning for action (i.e., solution finding, acceptance-finding). While the first two phases (understanding the problem and generating ideas) are very similar to Puccio's model, the third phase in this model (formulating the robot's behavior) is influenced by the fact that the action should be performed by an artificial agent (i.e., a robot). On the other hand, the last two phases of this model can be related to computational problem solving: the fourth phase (programming the behavior) describes the creation of executable code for the robot and the fifth phase (evaluating the solution) consists in the evaluation of the execution of the code (i.e., the robot's behavior).

The phases of the CCPS model

Based on the conceptual framework of ERS (Giang, Piatti, & Mondada, 2019), the CCPS model describes the different phases that students should go through when ERS is used for CT skills development (Fig. 2). It is a structure of five main phases that theoretically, in the most effective case, are completed one after the other and then repeated iteratively.

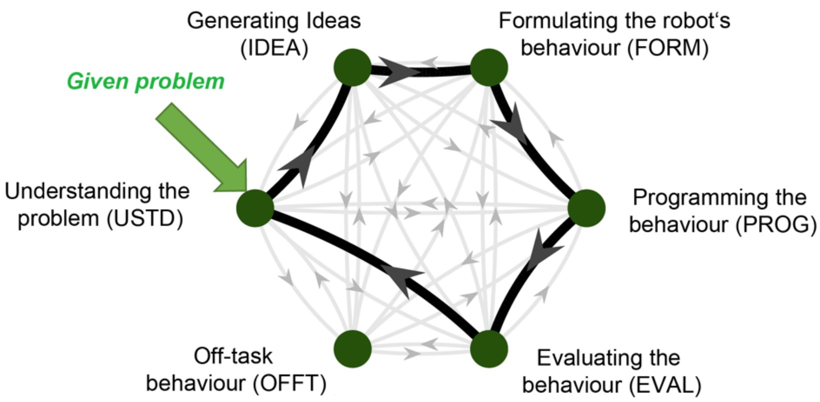

Fig.2 Phases and transitions of the CCPS model. The graph illustrates the six different phases (green dots) that students pass through when working on ER activities and all the possible transitions between them (gray arrows). The theoretically most efficient problem-solving cycle is highlighted in black. The cycle usually starts with a given problem situation that needs first to be understood by the problem solver (green arrow).

Understanding the problem (USTD) In this phase, the problem solver identifies the given problem (see COMP1 in the 5c21 framework of Romero et al. (2017)) through abstraction and decomposition (Shute et al., 2017) in order to identify the desired modification of the playground. Here, abstraction is considered as the process of "identifying and extracting relevant information to define main ideas" (Hsu et al., 2018). This phase takes as input the given problem situation, usually expressed in the language of the problem solver (e.g., natural language, graphical representations). The completion of this phase is considered successful if the problem solver identifies an unambiguous transformation of the playground that has to be performed by the robot. The output of the phase is the description of the required transformation of the playground.

Generating ideas (IDEA) The problem-solver sketches one or more behavior ideas for the robot that could satisfy the conditions given in the problem, i.e., modify the playground in the desired way. This phase requires a creative act, i.e., "going from intention to realization" (Duchamp, 1967). The input to this phase is the description of the transformation of the playground that has to be performed by the robot. The phase is completed successfully when one or more behaviors are sketched that have the potential of inducing the desired transformation of the playground. The sketches of the different behaviors are the output of this phase.

Formulating the behavior (FORM) A behavior idea is transformed into a formulation of the robot's behavior while considering the physical constraints of the playground and by mobilizing the knowledge related to the characteristics of the robot (see COMP4 in Romero et al. (2017)). To do so, the problem solver has to organize and model the situation efficiently (like in COMP2 in Romero et al. (2017)). The input to this phase is the sketch of a behavior, selected among those produced in the preceding phase. The phase is performed successfully when the behavior sketch is transformed into a complete formulation of the robot's behavior. The behavior formulation is expressed as algorithms in the problem solver's language, describing "logical and ordered instructions for rendering a solution to the problem" (Shute et al., 2017). This is considered the output of this phase.

Programming the behavior (PROG) In this phase, the problem solver creates a program (see COMP5 in Romero et al. (2017)) to transform the behavior formulation into a behavior expressed by the robot. Prerequisites for succeeding in this phase are the necessary computer science literacy and the knowledge of the specific programming language of the robot or its interface, respectively (see COMP3 in Romero et al. (2017)). Moreover, this phase serves for debugging (Shute et al., 2017), allowing the problem solver to revise previous implementations. The input to this phase is the robot's behavior expressed in the problem solver's language. The phase is performed successfully when the formulated behavior of the robot is completely expressed in the robot's language and executed. The output of this phase is the programmed behavior in the robot's language and its execution so that, once the robot is introduced to the playground, it results in a transformation of the playground.

Evaluating the solution (EVAL) While the robot performs a modification of the playground according to the programmed behavior, the problem solver observes the realized modification of the playground and evaluates its correspondence to the conditions of the problems and its adequacy in general. As described in Lumsdaine and Lumsdaine (1994), the problem solver acts as a "judge" in this phase. The input to this phase is the transformation of the playground observed by the problem solver. The observed transformation is compared with the conditions expressed in the given problem. Then, the problem solver has to decide if the programmed behavior can be considered an appropriate solution of the problem, or if it has to be refined, corrected, or completely redefined. This phase is therefore crucial to identify the next step of iteration (see Shute et al. (2017) and COMP2 in Romero et al. (2017)). As a result, the transitions in the CCPS model can either be terminated or continued through a feedback transition to one of the other phases.

Finally, an additional sixth phase, called **off-task behavior (OFFT)**, was included to account for situations where the problem solver is not involved in the problem-solving process. This phase was not considered a priori, however, the experiments with students showed that off-task behavior is part of the reality in classrooms and should therefore be included in the model. Moreover, in reality, transitions between phases do not necessarily occur in the order presented. Therefore, the model also accounts for transitions between non-adjacent phases as well as for transitions into the off-task behavior phase (light arrows in Fig. 2). In order to facilitate the presentation of these transitions, the matrix representation of the model is introduced hereafter (Fig. 3).

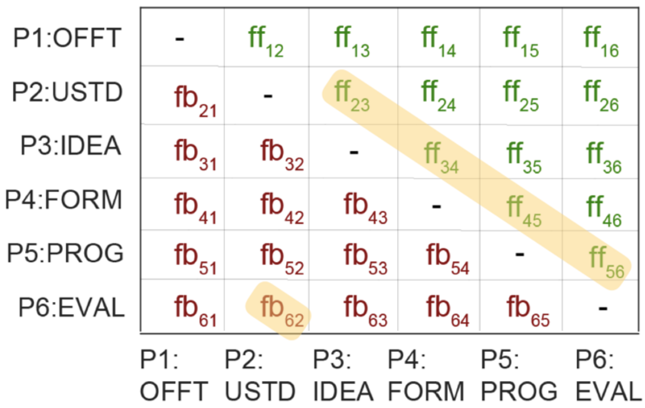

Fig.3 Matrix representation of the CCPS model. The figure depicts all phases of the CCPS model and transitions between them using a matrix representation. The rows i of the matrix describe the phases from which a transition is outgoing, while the columns j describe the phases towards which the transition is made (e.g., ff23 describes the transition from the phase USTD towards the phase IDEA). In this representation, feedforward transitions (i.e., transitions from a phase to one of the subsequent ones) are on the upper triangular matrix (green). Feedback transitions (i.e., transitions from one phase to one of the preceding ones) are on the lower triangular matrix (red). Self-transitions (i.e., the remaining in a phase) are not considered in this representation (dashes). The theoretically most efficient problem-solving cycle is highlighted in yellow (ff23–ff34–ff45–ff56–ff62).

In this representation, a feedforward (ff) is the transition from a phase to any of the subsequent ones and feedback (fb) is the transition from a phase to any of the preceding ones. Consequently, ffij denotes the feedforward from phase i to phase j, where i < j and fbij denotes the feedback from phase i to phase j, where j < i. With six states, there are in theory 15 possible feedforward (upper triangular matrix) and 15 possible feedback transitions (lower triangular matrix), as represented in Fig. 3. Although some of the transitions seem meaningless, they might however be observed in reality and are therefore kept in the model. For instance, it seems that the transition ff36 would not be possible, since a solution can only be evaluated if it has been programmed. However, especially in the context of group work, it might be possible that a generated idea is immediately followed by an evaluation phase, which was implemented by another student going through the programming phase. Finally, it can be assumed that feedback transitions usually respond to instabilities in previous phases. In this model, special emphasis is therefore placed on the cycle considering the transitions ff23-ff34-ff45-ff56-fb62 (highlighted in yellow in Fig. 3), which, as presented before, correspond to the theoretically most efficient cycle within the CCPS model.

Research question

As presented before, one common situation encountered in ER activities is the trial-and-error loop that in the CCPS model corresponds to an over-emphasis on feedforward and feedback transitions between PROG and EVAL phases. However, this condition might not be the most favorable for CT skill development, since the remaining phases (USTD, IDEA, and FORM) of the CCPS model are neglected. Consequently, this leads to the following research question: In a problem-solving activity involving educational robotics, how can the activation of all the CT processes related to the CCPS model be encouraged? In order to foster transitions towards all phases, the current study suggests to expressly generate an USTD-IDEA-FORM loop upstream so that students would not enter the PROG-EVAL loop without being able to leave it. To do so, a temporary blocking of the PROG phase (i.e., blocking the access to the programming interface) is proposed as an instructional intervention. Based on the findings of similar approaches implemented for inquiry-based learning (Bumbacher et al., 2018; Dillenbourg, 2013; Perez et al., 2017), the main idea is to introduce strategic pauses to the students to reinforce the three phases preceding the PROG phase. However, creating one loop to replace another is not a sustainable solution. With time, it is also important to adjust the instructional intervention into a "partial blocking," so that students can progressively advance in the problem-solving process. At a later stage, students should therefore be allowed to use the programming interface (i.e., enter the PROG phase); however, they should not be allowed to run their code on the robot, to prevent them from entering the trial-and-error loop between PROG and EVAL. Based on these instructional interventions, the current study aims at addressing the following research sub-questions:

- Does a non-instructional approach for ER activities (i.e., unlimited access to the programming interface) promote a trial-and-error approach?
- Does a blocking of the programming interface foster cognitive processes related to problem understanding, idea generation, and solution formulation?
- Does a partial blocking (i.e., the possibility to use the programming interface without executing the code on the robot) help students to gradually advance in the problem-solving process?

The resulting operational hypotheses are as follows:

- Compared to the control group, the students subject to the blocking of the programming interface (total then partial) will activate all the CT processes of the CCPS model.
- Compared to the test group, the students not subject to the blocking of the programming interface will mostly activate the PROG-EVAL phases of the CT processes of the CCPS model.

To test these hypotheses, an experiment using a test group and a control group was set up, with test groups that were subject to blocking of the programming interface and control groups that had free access to it.

Methods

The proposed CCPS model was evaluated in a research study with 29 primary school students (for details see "Participants" subsection). In groups of 2–3 students, the participants were asked to solve the robot lawnmower mission with the Thymio robot. In this activity, the robot has to be programmed in a way such that it drives autonomously around a lawn area, covering as much of the area as possible. Based on the CCPS model and the presented instructional interventions, two different experimental conditions were implemented for the activity and the students randomly and equally assigned to each condition. The activities of all groups were recorded on video, which subsequently were analyzed by two independent evaluators.

The robot lawnmower mission

The playground of the robot lawnmower mission consists of a fenced lawn area of 45cm × 45cm size (Fig. 4).

Fig.4 Playground of the robot lawnmower mission with Thymio. The playground consists of a wooden fence surrounding an area (45 × 45cm) representing the lawn. One of the nine squares represents the garage, the starting position of the mission (left). The task is to program the Thymio robot so that it passes over all eight lawn squares while avoiding any collisions with the fence (right).

The fence is constructed using wood, and the lawn area is represented by eight squares of equal size with an imprinted lawn pattern. A ninth square is imprinted with a brick pattern and placed at the bottom right corner of the area, representing a garage, i.e., the starting point of the Thymio lawnmower robot. In this activity, the students have to program a lawnmower behavior, which autonomously drives the robot out of its garage and in the best case, makes it pass over all eight lawn squares while avoiding any collision with the fence. The interest of using the Thymio robot to carry out this mission is twofold: on the one hand, this robot has many sensors and actuators (Mondada et al., 2017; Riedo, Chevalier, Magnenat, & Mondada, 2013; Riedo, Rétornaz, Bergeron, Nyffeler, & Mondada, 2012). On the other hand, among the different programming languages that can be used with Thymio, one is the graphical language VPL (Shin, Siegwart, & Magnenat, 2014). The VPL platform (Fig. 5) represents parts of the robot's language by graphical icons that can be directly interpreted by human problem solvers, particularly facilitating transitions from FORM to PROG phases. Students can implement their solutions by simple drag-and-drop actions, without the need of extensive efforts on learning complex syntax beforehand. However, in contrast to sequential programming languages, the robot cannot simply be instructed to move a certain distance towards a given direction. Instead, in the event-based programming language VPL, students have to reflect on how to use the robot's sensors and actuators to generate a desired behavior. The openness and uncertainty of the task thus requires the students to leverage many competences related to computational thinking.

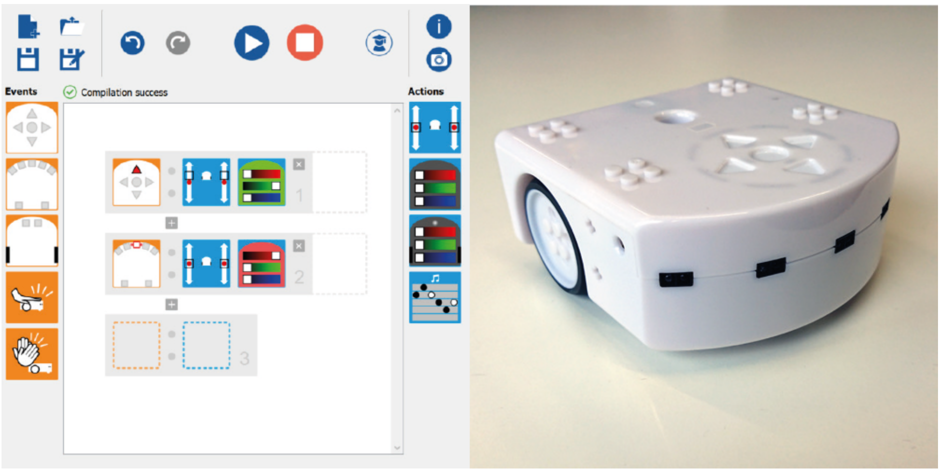

Fig.5 Illustration of proximity between the VPL programming interface and the Thymio robot. The figure illustrates the iconic representation of programming commands in the VPL programming platform (left). The icons were designed to be as close as possible to the characteristics of the Thymio robot (right).

Participants

A total of 29 primary school students (13 girls and 16 boys between 9 and 10 years old) participated in an experimental study with the purpose of evaluating the proposed CCPS model. Prior to the study, all students have been introduced to the Thymio robot and the VPL programming interface through several school lessons (1h per week for 12 weeks). The participation of the students in this study was approved by their guardians (parents) and class and school leaders (teachers and principal). A statement on ethics approval and consent was issued by The Coordination Committee for Educational Research in the Canton of Vaud (Switzerland).

Experimental procedure

At the beginning of the experimental session, all students were randomly assigned to groups of two or three. Each group of students was then randomly assigned to one of the two experimental conditions (test or control). The experimental procedures for the groups in each condition were different:

<u>Control groups :</u> The activity for the control groups started with a short introduction, where the goal and the rules of the mission were explained by one of the experimenters. The students were then given 40 min to implement their lawnmower robot. During the whole time period, they were allowed to use everything that was provided to them: the playground, the Thymio robot, and the VPL programming interface. No additional constraints were imposed.

<u>Test groups :</u> The experimental procedure for the test groups differed in the structure of the activity. Following the introductory speech, the activity started with 10 min of blocking of the programming interface. The students were given access to the playground and the Thymio robot, but they were not allowed to use the VPL programming platform. After this phase, the blocking was released, and the students were allowed to use everything for 10 min. This was followed by a partial blocking phase of 10 min, where the students had access to everything including the VPL platform, but they were not allowed to execute any code on the robot. For the last 10 min, the blocking was released again, and the students were allowed to use everything that was provided to them.

The study was conducted in two consecutive sessions of 45 min, one for each experimental condition. The test group (7 girls and 8 boys) started the mission first, while the control group (6 girls and 8 boys) went on a guided museum exhibition. After the completion of the first session, both groups switched. During each session, the five groups of the same experimental condition worked on the Thymio lawnmower mission simultaneously. Each group was provided a playground, a Thymio robot and a computer with the VPL platform installed. The sessions were supervised by two experimenters who provided technical support and addressed the students' questions regarding the task assignment. However, the experimenters did not provide any support regarding the solution of the lawnmower mission. Each group, as well as their interactions with the VPL platform and the playground, was recorded on video for later analysis.

Video analysis

Based on a socio-constructivist approach, this study relied upon in situ observations to capture the interactions of the students with each other as well as with the different cognitive artifacts (the robot, the interface, and the playground). The videos recorded from the experimental sessions were analyzed in several steps. Prior to individual analyses, two evaluators met to discuss and agree on appropriate observables (visual and verbal) indicating transitions towards the different phases of the CCPS model. Therefore, both evaluators first analyzed various prerecorded ER activities together. The videos were recorded from different kinds of ER activities and allowed to establish criterion standards (Sharpe & Koperwas, 2003) that are not limited to one specific ER activity. The whole procedure was aimed at streamlining the way both evaluators would perform their individual analyses. Subsequently, both evaluators performed the behavioral analysis independently, sequentially mapping the behaviors of the students during the robot lawnmower activity to the different phases of the CCPS model. The mappings were made under the assumption that a student can only be in one of the six phases of the CCPS model at a time. Each evaluator performed the mapping based on their interpretation of the behavior of the students, while considering the criterion standards that have been established beforehand. Transitions to the first three phases of the CCPS model were mainly mapped based on the students' verbalizations, such as "How can we do that?" (USTD), "Ah, I have an idea!" (IDEA) or "If this sensor detects the wall, the robot turns left" (FORM). In contrast, transitions to the last two phases were mostly based on visual observations (e.g., a student starting to use the computer (PROG) or a student watching the Thymio robot after executing the program (EVAL)). Students who were clearly not involved in the activity were mapped to the off-task behavior phase (OFFT). Two state graphs were created for each student (one by each evaluator) using a software dedicated to the creation of activity chronicles such as Actograph (SymAlgo Technologies, Paris, France) and a numerical computing tool such as Matlab (MathWorks, Natick, Massachusetts, USA). Following this step, both evaluators compared their state graphs against each other and discussed any major discrepancies between their evaluations. Major discrepancies were considered segments in the state graphs in which both evaluators did not agree on the same behavior for more than 1 min. The corresponding video scene was reviewed by both evaluators together to achieve a mutual decision. Based on this decision, the state graphs of the evaluators were modified accordingly. Subsequently, the continuous state graphs of both evaluators were discretized into equally spaced time segments of one second. Finally, Cohen's Kappa was computed for the discretized pair of state graphs of each student, in order to validate the inter-rater reliability of the performed video analyses. Therefore, confusion matrices were created for the observations made by both researchers. Agreement between both evaluators was quantified by the number of times both evaluators agreed on mapping the same phase of the CCPS model to a student's behavior. The Kappa values were then calculated for the observations made for each student, using the formula presented in (Bakeman & Gottman, 1997) and taking into account the proportion of agreement observed and the proportion expected by chance. The range of the values for Cohen's Kappa was $0.59 < k < 0.84$ (Fig. 6), which according to the literature (Landis & Koch, 1977) can be interpreted as a substantial agreement between both evaluators. Finally, the state graphs created by the first evaluator were used to perform further analyses. Based on these state graphs, the time spent in each state of the CCPS model was computed for each student, as well as the total number of transitions made between different phases. Overall, 2162 phase transitions were mapped for the total of 400 min of recordings: 1072 transitions for the test groups and 1090 for the control groups.

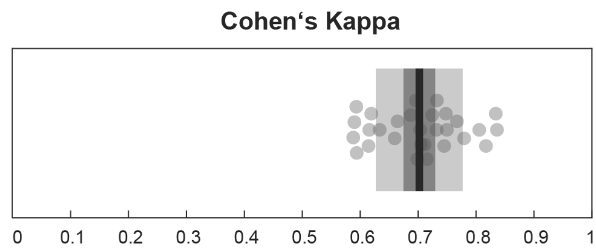

Fig.6 Cohen's Kappa values for two independent evaluators. Dots indicate Cohen's Kappa values calculated for each student based on the independent observations of two evaluators. The dark horizontal line indicates the mean value, dark gray areas one standard deviation, and light gray areas the 95% confidence intervals.

Results

Transition matrices were created for each student, illustrating the changes from one state of the CCPS model to another during each quarter of the activity (first, second, third, and last 10 min). All transitions made by the students in each condition (test and control) were then summed up to analyze the overall dynamics of the two experimental groups (Fig. 7). Moreover, the total time spent in each phase was analyzed for both groups during each quarter of the activity. The transition matrices for the control groups showed similar dynamics for all quarters of the activity. Transitions were found on the upper and lower triangular part of the matrices, highlighting the occurrences of both feedforward and feedback transitions. Most occurrences were found for transitions between PROG and EVAL phases. In contrast, transitions from and towards USTD, IDEA, FORM, and OFFT phases appeared to be less frequent. When looking at the total time spent in each phase, a similar trend was observed: especially in the first three quarters of the activity, students of the control group predominantly spent their time in PROG and EVAL phases (on average 22 out of 30 min), while USTD, IDEA, FORM, and OFFT phases were observed less frequently (8 out of 30 min). In the last quarter of the activity, PROG and EVAL remained more prevalent compared to USTD, IDEA, and FORM phases; however, a similar amount of time was now also spent on off-task behavior (OFFT, 3 out of 10 min).

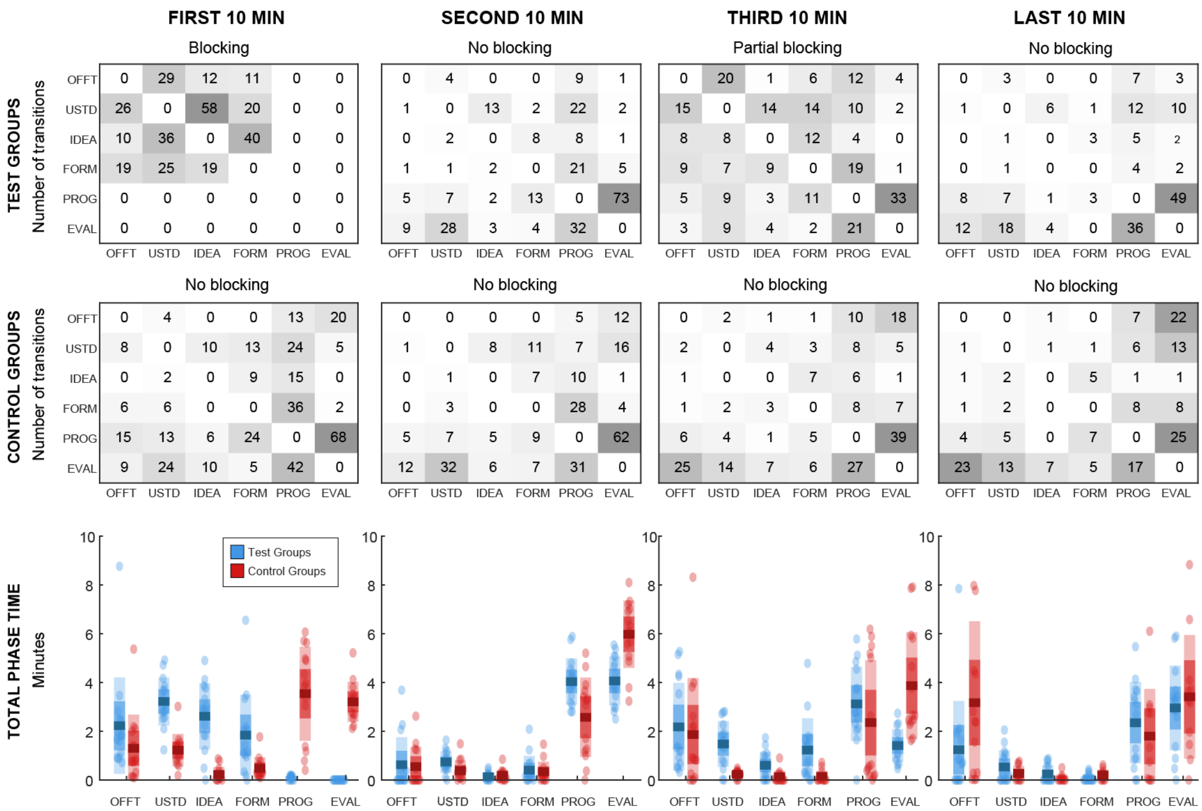

Fig.7 Transition matrices and total phase times. The top rows show the transition matrices for the test (first row) and control groups (second row) for the first, second, third, and last 10 min of the activity. The entries in the matrices denote the total number of transitions made between the different phases for each group. Transitions with higher occurrences are highlighted with darker colors. The last row shows the total time spent in each phase by both groups for the four quarters of the activity. Colored dots show data points for each student of the test (blue) and control (red) groups. Dark horizontal lines indicate the mean values, dark-colored areas one standard deviation, and light-colored areas the 95% confidence intervals.

Also, in test groups, both feedforward and feedback transitions were observed; however, the dynamics varied during the different quarters of the activity. The behavior in the second and last quarter (no blocking conditions) was very similar to the behavior of the control groups: the great majority of transitions was observed between PROG and EVAL phases, while transitions to and from other phases were comparatively lower. However, when looking at the transition matrices for the first and third quarter of the activity, remarkable differences were found. Due to the blocking of the VPL programming interface in the first quarter, students were not able to enter any of the PROG or EVAL phases and were thus forced to shift their attention towards the remaining phases. For the third quarter, on the other hand, a more even distribution among all phases was found. Since the partial blocking condition allowed the students to work with the VPL platform (without the possibility to send the program to the robot), transitions to PROG phases could be observed. Moreover, since students have already programmed their robot during the previous quarter of the activity, they were also able to make transitions to EVAL phases.

Interestingly, there was a high number of transitions between PROG and EVAL phases, indicating a rigorous debugging of the students' previous implementation, since new implementations could not be executed and tested (i.e., trial-and-error was not possible). The blocking conditions also influenced the total time the students spent in each of the phases. Compared to the control group, there was a more even distribution among the phases for the first three quarters of the activity. On average, students spent 13 out of 30 min in PROG and EVAL phases and 12 out of 30 min in USTD, IDEA, and FORM phases. During the first three quarters, the times spent on off-task behavior (OFFT) by the test groups were very similar to the ones by the control groups. However, in contrast to the control groups, off-task behavior also remained on a similar level in the last quarter of the activity.

In order to further investigate the effect of the initial blocking condition, transition graphs were generated for the first 10 min of the activity (Fig. 8).

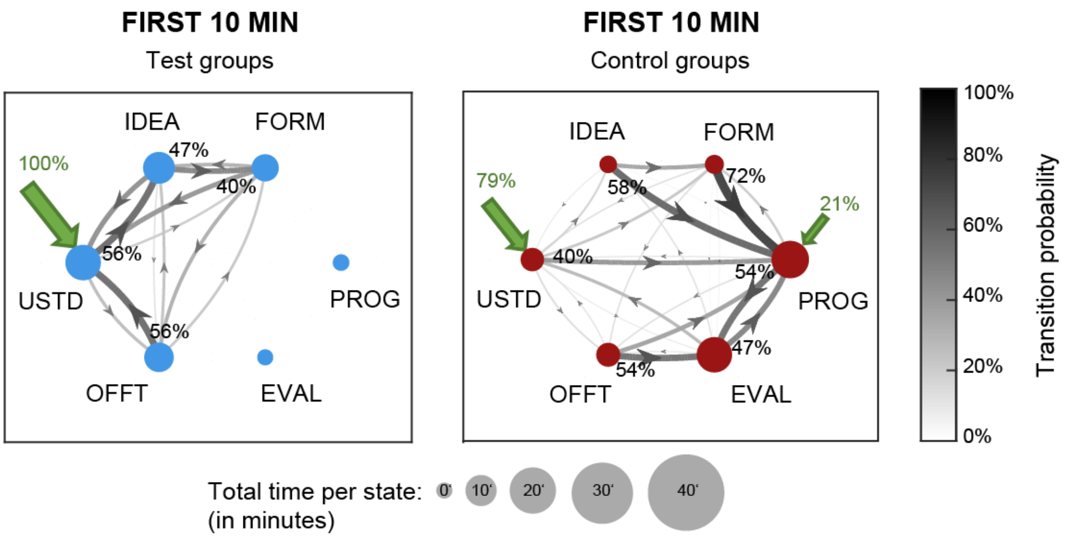

Fig.8 Initial transition graphs for test and control groups. The figure shows the transitions graphs for both groups for the first 10 min of the activity. The green arrows indicate the probabilities for the first transitions of the activity. The size of the dots, representing the six phases of the CCPS model, is proportional to the amount of time spent by the groups in each phase. The gray arrows represent the transition probabilities between phases. Higher transition probabilities are represented by thicker and darker lines. The value for the most probable outgoing transition for each phase is given next to the corresponding arrow.

These graphs depict the transition probability from one phase to another for both groups as well as the total time spent in each phase. Moreover, the initial transition for each student was determined, i.e., the first phase they entered when the activity started. In the test groups, all fifteen students started the activity with the USTD phase, corresponding to the start of the theoretically most efficient cycle of the CCPS model (see Fig. 2). In the control groups, this behavior was not observed for all students. Although the majority started with the USTD phase, three of the fourteen students entered the activity by directly going to the PROG phase.

Moreover, when comparing the transition probabilities between the phases, remarkable differences were found for both groups: the results showed that the transition graph for the test groups matched well with the first part of the theoretically most effective cycle in the CCPS model. For these groups, the blocking condition hindered any transition from and towards PROG and EVAL phases. Starting from the USTD phase, students would therefore most likely continue with IDEA, then FORM phases, and then eventually return to USTD for another iteration. Although other feedforward and feedback transitions were observed, they appeared to be less likely. If students showed off-task behavior, they would most likely return to the activity through the USTD phase.

The total time spent in each of the four phases was evenly distributed. For the control groups on the other hand, no blocking conditions were imposed. From the transition graph, it can be seen that the activities of the control groups were more centered around PROG and EVAL phases. Once the students would enter the PROG phase, the most likely transition was towards the EVAL phase and vice versa. Although transitions towards other phases were observed, the probability of leaving this PROG-EVAL loop was comparatively low. Moreover, the effect of this loop was reinforced by the fact that most transitions from USTD, IDEA, FORM, and OFFT phases were directed towards PROG or EVAL phases, resulting in an uneven distribution of the time spent in each phase: during the first 10 min of the activity, the students of the control groups spent almost 7 min in PROG and EVAL phases and less than 2 min on USTD, IDEA, and FORM phases.

In order to illustrate the dynamics at individual levels, the state graphs, transition matrices, and transition graphs for one exemplary student of each group are presented (Fig. 9).

The data is shown for the whole 40 min of the activity. It can be observed that the student from the control group immediately started the activity by jumping into the PROG phase. Throughout the activity, the student spent most of the time only in PROG and EVAL phases, sporadically transitioning to one of the other phases that were then followed by transitions back to the PROG-EVAL loop. The inclination towards these phases is highlighted in the corresponding transition graph, which clearly demonstrates that this student strongly neglected the preceding USTD, IDEA, and FORM phases. The student from the test group on the other hand showed a more balanced distribution among the five phases of the CCPS model. Indeed, the transition matrix of this student showed a more even dispersion for the transitions towards different phases. Interestingly, a high number of transitions were found for the path USTD–IDEA–FORM–PROG–EVAL–USTD, indicating an inclination towards the theoretically most efficient cycle of the CCPS model. From the state graphs, it can also be observed that the student from the test group performed more playground interactions (11 times), i.e., interactions with the robot or the lawn area, compared to the student from the control group (2 times). A similar result was observed when analyzing the overall data for playground interactions of each experimental group (in total 93 interactions for the test groups and 59 interactions for the control groups).

Finally, the performance of each group's lawnmower was quantified by the highest number of lawn squares that the robot managed to cover without collision. The results showed that three groups (two tests and one control) managed to complete the task, covering all eight lawn squares with their lawnmower robot. Five groups (three tests and two controls) covered six squares and two groups (both control) covered only 4 squares. The number of squares was only quantified for trajectories that started from the garage and that were not random.

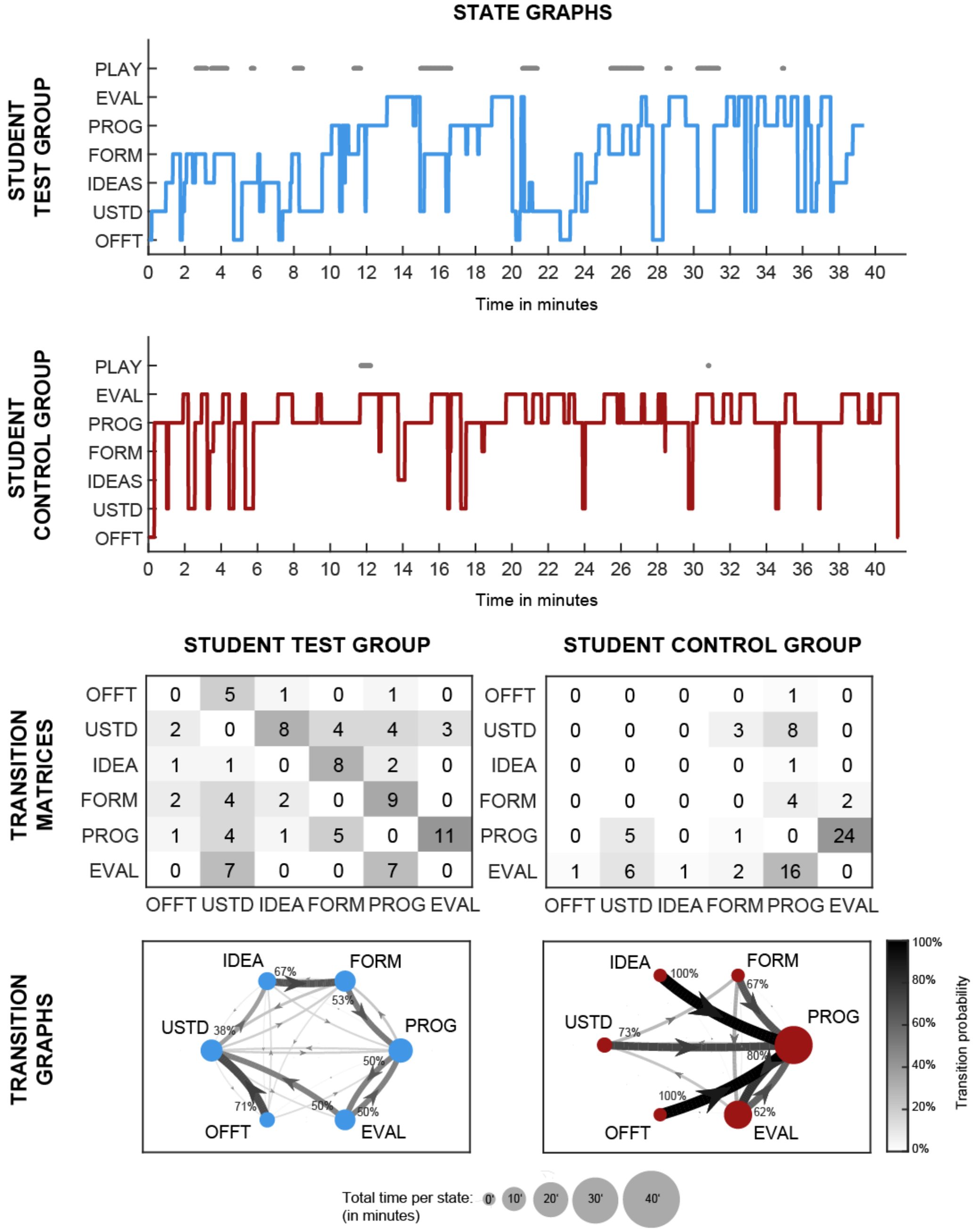

Fig.9 State graphs, transition matrices, and transition graphs for two example students. The figure shows the data for two students, each exemplifying what was observed in the test and control groups, respectively. The top rows show the complete state graphs for the student from the test (first row) and the control group (second row), displaying in which phase each student was at each moment of the activity. Moreover, the students' interaction with the playground is highlighted (PLAY). The third row shows the transition matrices for both students for the whole 40 min of the activity. The entries in the matrices denote the total number of transitions made between the different phases for each student. The last row shows the transitions graphs for both students for the whole 40 min of the activity.

Discussion

The effect of non-instructional approaches for ER activities

Usually in educational robotics activities, students work in pairs or groups to solve one or more problems, especially when these activities are aimed at the development of computational thinking skills students are faced with open-ended problems that they have to solve in collaboration. By doing so, they benefit from the "dynamic feedback inherent in dialog and the creation of cognitive conflict" (Hoyles, 1985). In many cases, teachers let the students work in the project without any particular constraints (Buss & Gamboa, 2017; Sadik et al., 2017). In the present study, the control groups were left in this situation which corresponds to a non-instructional approach for ER activities in classrooms. However, the results of this study showed that under these circumstances, students spent most of their time in phases related to programming and evaluating. It was observed that, once entered in this loop, students would hardly change their strategies and barely work on any of the other phases presented in the CCPS model. This result suggests an answer to the first research question addressed in this study:

Does a non-instructional approach for ER activities (i.e., unlimited access to the programming interface) promote a trial-and-error approach?

Indeed, the students from the control groups spent on average almost two-thirds of their time in programming and evaluating which does not leave much time to develop other skills (understanding the problem, generating ideas, formulating a behavior). This large amount of time spent is thus a clue showing that students were plunged in a trial-and-error loop. Moreover, the results showed that the probability of leaving this PROG-EVAL loop was low and that it proves a lack of organization in the strategy: students should go from trial-and-error to systematic testing providing "evidence of problem decomposition" (Shute et al., 2017). In the current study, the population had the same background and knowledge: at the age of 9 to 10 years, such a behavior is usual while the students are just in the process of building proper problem-solving strategies. Indeed, as soon as the students from the test groups had access to the computer, they also spent a lot of time in the PROG-EVAL phases. Based on these results, the main conclusion is that in non-instructional classroom approaches where the teacher does not intervene in the instructional design of ER activities and does not put constraints on the students, the latter stays most of the time in a PROG-EVAL loop.

The effect of blocking and partially blocking the programming interface.

In this study, the test groups had undergone an instructional intervention while they had to solve a problem involving programming. Indeed, in order to prevent them from immediately entering the PROG-EVAL loop, a blocking of the programming interface was imposed in order to require them to shift their attention to the other phases of the CCPS model. The second intervention condition that was tested was equally verified by this experimental study:

Does a blocking of the programming interface foster cognitive processes related to problem understanding, idea generation, and solution formulation?

Indeed, in the test groups, students were forced to shift their attention towards other phases since their possibilities to enter PROG and EVAL phases were limited by the given constraints. It was observed that given the same amount of time, the test groups better distributed their cognitive efforts in total (measured by a similar amount of time spent in USTD-IDEA-FORM compared to PROG-EVAL). Although no specific instructions were given to the students, their behavior tended to converge towards the theoretically most efficient cycle of the CCPS model. Students started the activity by trying to understand the problem, and they then generated ideas and subsequently suggested formulations of the behavior of the robot. These iterations can be explained by the feedback inherent to dialog which occurs during collaborative situations (Hoyles, 1985). Whereas it is not an unusual behavior to go directly for programming (Buss & Gamboa, 2017; Sadik et al., 2017), no results were found a priori in state-of-the-art literature considering the behavior observed under a blocking condition of the programming interface. The results of this study therefore raise the question of how this blocking condition effectively influences the learning outcomes. It is assumed that the fact that students perform more transitions towards USTD, IDEA, and FORM phases would help them on the development and reflection of their problem-solving process. As shown in previous work on inquiry-based learning (Bumbacher et al., 2018; Dillenbourg, 2013; Perez et al., 2017), introducing these kinds of strategic pauses may help students to better reflect prior to taking actions. Applying this principle to ER activities could substantially enhance the learning outcomes, especially with regard to the development of CT skills. Indeed, in the present study, students from the test group iterated the USTD-IDEA-FORM loop (performing both feedforward and feedback transitions between those phases) in the first 10 min of the activity, arguing and anticipating what could happen afterwards. This cognitive state in which they dived into seems to allow students to distance themselves from the programming act to better reflect on the “creative act” (Duchamp, 1967).

Another finding related to the effect of this instructional intervention is that test groups seemed to interact more with the playground and the robot than the control groups. As the latter favored a PROG-EVAL loop, they were more likely to be immersed in the programming interface. In contrast, since the test groups did not have access to the computers at the beginning, they appeared to be more inclined towards using the playground and the robot as means to express their thoughts and findings. This mediation is a key element on which it is then possible to intervene. In fact, this is what happened when the experimental condition was altered in a partial blocking at the beginning of the second half of the experiment. The findings from the study allowed verification of the third intervention hypothesis:

Does a partial blocking (i.e., the possibility to use the programming interface without executing the code on the robot) help students to gradually advance in the problem-solving process?

The transition from a full blocking of the programming interface to a partial blocking can be considered as a way to provide scaffolding. Thanks to this scaffolding, during half of the time, the students were able to build a well-settled strategy to solve the problem and they were therefore mostly able to iterate the theoretically most efficient cycle of the CCPS model (USTD–IDEA–FORM–PROG–EVAL–USTD). Moreover, during this partial blocking, the high number of transitions between PROG and EVAL phases suggests a rigorous debugging of previous implementations, an element which has been considered important for the development of CT competencies (Bers et al., 2014; Shute et al., 2017). The students iteratively worked on the commonly identified issues and still had to predict possible behaviors because the partial blocking prevented them from the execution of the new program code. This condition could be considered beneficial to help students develop skills related to CT. For instance, among the test groups, during the partial blocking, two students decided to set up a writing strategy for programming the robot. While they were told that they could use the programming interface without executing their program, they decided to keep their paper strategy arguing that “it’s the same.” This example shows the effect of fading from a blocking to the partial blocking, and these experimental conditions can therefore be considered an interesting scaffolding tool for teachers.

The overall performances of the implemented lawnmower robots illustrated higher task completion rates for the test groups. All five test groups managed to cover at least six lawn squares and two of them completed the mission covering all eight squares. In the control groups instead, there were two groups who did not manage to cover more than four squares and two groups not more than six. Although one group managed to finish the mission using a pure trial-and-error approach, the effective CT skills development for this group might be questionable. Indeed, previous work has argued that trial-and-error strategies may not be considered optimal, since they may “support task completion but not skills development” (Antle, 2013).

Off-task behavior as part of the activity

While designing the CCPS model, it was initially not obvious to include off-task as a separate phase of the model. However, while observing the students during the experiment, it appeared that the off-task behavior (OFFT) was indeed part of the reality in classrooms. Consequently, it was decided to include it as an additional phase of the model. It appeared that the dropout from the activity was a residue that was found in both the test and control groups. However, the distribution of this residue was not equivalent between the two types of groups. In contrast to the test groups, off-task behavior increased significantly during the last quarter of the activity (after 30 min) for control groups. It seems that the working modalities in the test groups (i.e., blocking and partial blocking) may foster engagement in the task in a longer term, compared to the unconstrained modality for the control groups. As described, the scaffolding in the access to programming allows students to have a progression over time. This may facilitate their immersion in the activity and thus results in more effective learning time. In this sense, it seems that the implementation of the blocking conditions can also minimize off-task behavior in classroom situations, which could possibly lead to more efficient learning activities.

Conclusion

The findings reported in this article have provided empirical evidence that (i) a non-instructional approach for educational robotics activities (i.e., unlimited access to the programming interface) can promote a trial-and-error behavior; (ii) a scheduled blocking of the programming interface can foster cognitive processes related to problem understanding, idea generation, and solution formulation; (iii) a progressive adjustment of the blocking of the programming interface can help students in building a well-settled strategy to approach educational robotics problems and therefore may represent an effective way to provide instructional scaffolding. Taking these findings into account, this study provides initial evidence on the need for specific instructional interventions on ER activities and illustrates how teachers could use the proposed model to design ER activities aimed at CT skill development. The findings of this study thus allow to make a transition from theoretical to more operational frameworks as recommended by Ioannou and Makridou (2018). The CCPS model is indeed inspired by existing CT models (Romero et al., 2017; Shute et al., 2017), but it makes a distinct contribution regarding the transfer to the classroom by providing teachers with explicit guidance on the implementation, as previously recommended by Atmatzidou and Demetriadis (2016). Indeed, this study offers to teachers and researchers a conceptualization of five cognitive states (USTD–IDEA–FORM–PROG–EVAL) which is adapted to ER activities and K-5 students. In the present work, the main pedagogical lever that has been manipulated was the blocking of the programming interface. This intervention proved to be an effective way to help students cover a more complete spectrum of CT competencies, in contrast to a non-instructional modality, in which they mainly focus on their programming skills. As a matter of fact, this intervention can be easily implemented by teachers regardless of the type of robot used. Consequently, this study also addresses the lack of research on CT for K-5 classrooms, particularly grades 3 and 4, i.e., students of age between 8 and 10 years old. However, the presented findings are not limited to this age range and may possibly be extended to younger and older students. Finally, the establishment of this model and especially of its mechanics could appear as a step forward in the implementation of the CT in the classroom through ER activities.

Limitations and future work

Although the results of this study appear to be promising, further studies are needed to draw more substantial conclusions. Due to school regulations, access to classrooms is limited for research purposes, hence in this study, the experiments were conducted with a small sample size. Nevertheless, considering the 2162 mapped transitions, this size could be considered sufficient for the purpose of this research, which is namely to verify the present model. However, as the main goal of the CCPS model is to support teachers in the design, implementation, and evaluation of ER activities, future work should investigate whether teachers really perceive an added value of the model for their teaching activities. Moreover, other intervention hypotheses could be explored and tested, in order to demonstrate more exhaustive validity of the model. Furthermore, in order to present evidence for the effectiveness as a reference model for ER activities, future longitudinal studies should investigate the effective learning gains evoked by the interventions proposed by the model. In this regard, the findings of the present study may provide a good starting point for the design and executions of such studies.

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Authors' contributions

M.C. designed the model, carried out experiments, analyzed data, and wrote the paper; C.G. designed the model, carried out experiments, analyzed data, and wrote the paper; A.P. designed the model, carried out experiments, and wrote the paper; F.M. designed the model and wrote the paper. The author(s) read and approved the final manuscript.

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Availability of data and materials

The data sets generated and analyzed during the current study are not publicly available due to the sensitivity of the data of the under-age participants but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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SUPPLEMENTARY MATERIAL

Observation grid of students' activity in a CCPS situation in educational robotics:

CCPS Phases	**Phase Code**	**Phase Input**	**Phase Description**	**Phase Output**	**Criterion standards for the observed behaviour**
Understanding the problem	USTD	The given problem situation which is usually expressed in the language of the problem solver (e.g., natural language, graphical representations).	In this phase, the problem solver identifies the given problem through abstraction and decomposition in order to identify the desired modification of the playground. The completion of this phase is considered successful if the problem solver identifies an unambiguous transformation of the playground that has to be performed by the robot.	The description of the required transformation of the playground.	- problem identification - identifying and extracting relevant information to define main ideas - collecting information from the playground - students' verbalizations, such as "Why…?", *"How can we do that?"* - manipulating the robot - looking at the different artefacts
Generating Ideas	IDEA	The description of the transformation of the playground that has to be performed by the robot.	The problem-solver sketches one or more behavior ideas for the robot that could satisfy the conditions given in the problem, i.e., modify the playground in the desired way. The phase is completed successfully when one or more behaviors are sketched that have the potential of inducing the desired transformation of the playground.	The sketches of the different behaviors.	- evidence of a creative act, i.e., going from intention to realization" (e.g., eagerness towards one of the artefacts, often associated with eureka verbalization such as "I know!", "yes!", *"Ah, I have an idea!"*). - robot handling test - sketches or designs
Formulating the behaviour	FORM	The sketch of a behavior, selected among those produced in the preceding phase.	A behavior idea is transformed into a formulation of the robot's behavior while considering the physical constraints of the playground and by mobilizing the knowledge related to the characteristics of	The behavior formulation is expressed as algorithms in the problem solver's language, describing logical and	- negotiation and formulation of the sequencing, the capabilities of the machine, its interactions with the other artefacts in the playground - students' verbalizations, such as *"If this sensor de-*

			the robot. To do so, the problem solver has to organize and model the situation efficiently. The phase is performed successfully when the behavior sketch is transformed into a complete formulation of the robot's behavior.	ordered instructions for rendering a solution to the problem.	*tects the wall, the robot turns left", "First, the robot will…, then it will…"*
Programming the behaviour	PROG	The robot's behavior expressed in the problem solver's language.	The problem solver creates a program to transform the behavior formulation into a behavior expressed by the robot. Prerequisites for succeeding in this phase are the necessary computer science literacy and the knowledge of the specific programming language of the robot or its interface, respectively. Moreover, this phase serves for debugging, allowing the problem solver to revise previous implementations. The phase is performed successfully when the formulated behavior of the robot is completely expressed in the robot's language and executed.	The programmed behavior in the robot's language and its execution so that, once the robot is introduced to the playground, it results in a transformation of the playground.	- student starting to use the computer - local or remote programming? - local or remote code execution? - reluctance to press the button to run the program - stop the program - delete the program
Evaluating the solution	EVAL	The transformation of the playground observed by the problem solver.	While the robot performs a modification of the playground according to the programmed behavior, the problem solver observes the realized modification of the playground and evaluates its correspondence to the conditions of the problems and its adequacy in general. The problem solver acts as a "judge" in this phase.	The decision to iterate (if the programmed behavior has to be refined, corrected, or completely redefined.) or not (if the programmed behavior is considered an appropriate solution of the problem)	- watching the robot after executing the program - back and forth between the programming interface and the playground - identify the next step of iteration
Off-Task behavior	OFFT (or none)		situations where the problem solver is not involved in the problem-solving process		- clearly not involved in the activity - looking at other groups - leaving the group

Paper #3

Chevalier, M., Giang, C., Laila El-Hamamsy, L., Bonnet, E., Papaspyros, V., Pellet, J.-P., Audrin, C., Romero, M., Baumberger, B., Mondada, F. (*under review*). The role of feedback and guidance as pedagogical interventions to foster computational thinking in educational robotics learning activities for primary school.

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The role of feedback and guidance as intervention methods to foster computational thinking in educational robotics learning activities for primary school

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Abstract.

Computational thinking (CT) is considered an emerging competence domain linked to 21st-century competences, and educational robotics (ER) is increasingly recognised as a tool to develop CT competences. This is why researchers recommend developing intervention methods adapted to classroom practice and providing explicit guidelines to teachers on integrating ER activities.

The present study thus addresses this challenge. Guidance and feedback were considered as critical intervention methods to foster CT competences in ER settings. A between-subjects experiment was conducted with 66 students aged 8 to 9 in the context of a remote collaborative robot programming mission, with four experimental conditions. A two-step strategy was employed to report students' CT competence (their performance and learning process). Firstly, the students' CT learning gains were measured through a pre-post-test design. Secondly, video analysis was used to identify the creative computational problem-solving patterns involved in the experimental condition that had the most favourable impact on the students' CT scores. Results show that delayed feedback is an effective intervention method for CT development in ER activities. Subject to delayed feedback, students are better at formulating the robot behaviour to be programmed, and, thus, such a strategy reinforces the anticipation process underlying the CT.

Keywords. *Collaborative learning, Elementary education, Improving classroom teaching, Teaching/learning strategies, 21st-century abilities*

1. Introduction

There is a consensus nowadays that Computational Thinking (CT) is a multidimensional construct that consists of three widely spread dimensions (Tikva & Tambouris, 2021; Guggemos, 2021; Zhang & Nouri, 2019): i) computational perspective (i.e., "the perspectives designers form about the world around them and about themselves", Brennan and Resnick, 2012, p.1), ii) computational concepts (i.e., "the concepts designers engage with as they program", ibid.), and iii) computational practices (i.e., "the practices designers develop as they engage with the concepts, such as debugging projects or remixing others' work", ibid.). Nevertheless, in their review, Lye and Koh (2014) deplore the lack of a specific intervention approach to foster both the "computational practices" and "computational perspective" dimensions, with most CT interventions focusing on computational concepts (Li et al., 2020).

Converging with problem-solving abilities (Yadav, 2016), the computational perspective dimension appears to be the most transversal dimension constituting CT. Indeed, this dimension is composed of elements such as identifying a situation, understanding a problem, and modelling a solution (Romero et al., 2017). All these elements are competences present in other disciplines. Therefore, intervention approaches favouring this CT dimension should be based on approaches already widely used in pedagogy. As guidance is considered the most common and efficient instructional approach to sustain the student learning process (Kirschner et al., 2006; Atmatzidou & Demetriadis, 2012; Sapounidis & Alimisis, 2020), this intervention method should also be relevant in the context of CT.

As far as the computational practice dimension is concerned, it is often addressed through programming (Brackmann et al., 2017), which represents the phase of reification of what has been thought upstream. Unfortunately, the programming act, or any form of experimentation in itself, is not sufficient to ensure learning (Mayer, 2004), with explicit guidance being required (Kirschner et al., 2006) to help students reflect on their practices. Moreover, during the human-machine interaction while programming, feedback is of first-order to guarantee the good development of the practice (Smith & Lipnevich, 2018; Wise & O'Neill, 2009; Shute, 2008; Hattie & Timperley, 2007) and depending whether it is immediate or delayed the effects may vary.

In response to the shortcomings put forward by Lye & Koh (2014), we propose to study the role of feedback and guidance as pedagogical interventions to foster computational thinking in educational robotics learning activities for primary school. Hence, we ask the following interrelated research questions:

1) Between guidance and feedback, which of these two intervention methods most favourably fosters CT competence for 8-9-year-old students?

2) How do(es) that most favourable intervention method(s) impact students' problem-solving strategies?

In the following sections, we detail the experiment we conducted to address these two questions. Section 2 first presents the state of the art of the types of guidance and feedback and their effect in ER problem-based learning activities to foster CT. Section 3 presents our experiment's details. Section 4 examines the data collected and shows, on the one hand, the positive impact of using delayed feedback on CT and, on the other hand, that cognitive processes and learning outcomes differ according to the type of feedback used (immediate or delayed). Finally, Section 5 presents a conclusion of this work.

2. Background

This section examines the literature concerning guidance (section 2.1) and feedback (section 2.2), which are considered effective intervention methods to foster CT competences in ER settings.

2.1. Guidance as an intervention method to foster CT in ER settings

2.1.1. The purpose of guidance in education

Guidance is the act of guiding students to construct knowledge (scaffolding process, Vygotsky, 1978). Through the tutorial interaction (Bruner, 1983), teachers try to get students to solve a problem that they cannot solve alone. This help provided by teachers is then gradually withdrawn (fading of scaffolding process). Intending to make students actors of their learning, teachers can resort to various guidance acts such as reformulating the problem, decomposing, demonstrating… provided through multiple media (lectures, videos, computer-based presentations…, Clark et al., 2012). Hence, guidance varies according to an intensity cursor (minimal vs strong) and a wide range of action types.

2.1.2. Variating guidance in problem-solving

The variation of guidance depends on whether the students are novices or experts (Clark et al., 2012). Indeed, novices or students "dealing with novel information [so using their working memory] should be explicitly shown what to do and how to do it, and then have an opportunity to practice doing it while receiving corrective feedback" (Clark et al., 2012, p.7). Contrariwise, as expert students benefit from "both their working memory and all the relevant knowledge and skill stored in long-term memory" (Ibid., p.9), they can still learn with minimal guidance.

2.1.3. The case of trial-and-error

The distinction between novices and experts highlights a specific case in computer problem-solving: the trial-and-error strategy. Indeed, as stated by Clark et al. (2012):

> « Solving a problem requires searching for a solution, which must occur using our limited working memory. If the learner has no relevant concepts or procedures in long-term memory, the only thing to do is blindly search for possible solution steps that bridge the gap between the problem and its solution" (p.10).

This blind search may refer to a blind trial-and-error strategy (i.e., a quick alternate between the programming and evaluation/test phases) in the specific context of ER. Chevalier and Giang et al. (2020) refer to this behaviour as "an over-investment in programming concerning other problem-solving tasks during ER activities" (p.2). They found that "a non-instructional approach for educational robotics activities (i.e., unlimited access to the programming interface) can promote trial-and-error behaviour" (p.16). Such an unfettered exploration leads to behavioural activity during learning which may not systematically imply cognitive activity (Mayer, 2004). Indeed, without guidance, students may not actively think while problem-solving, tempted by the natural strategy of trial-and-error rather than reflecting on action (Biesta & Burbules, 2003).

Thus, trial-and-error is a usual approach for novices, whereas experts are likely to use domain-specific strategies to solve problems (Mayer, 2004). Nevertheless, novices may go beyond such an approach and try more rational approaches (Alimisis, 2019). Despite being novice or expert, Merisio et al. (2021) state that "all robotic programming is trial-and-error and reasoned at the same time" (p.199). Namely, they recall that AI problem solving uses blind search methods, i.e., considering all the possible paths until a "right" one is found. However, such a strategy is time and memory consuming.

In sum, explicit instructional guidance is more effective and efficient than partial guidance (Kirschner et al., 2006; Sweller et al., 2007). Meanwhile, minimal guidance techniques can reinforce or practice previously learned material (Clark et al., 2012). Whether it is minimal or not, the type of guidance must be described.

2.1.4. The type of guidance in ER

As CT is considered a problem-solving tool (CSTA, 2011), it is relevant to identify the effect of guidance in problem-solving. To date, Tikva and Tambouris (2021) have listed in the literature 12 studies out of 37 that refer to scaffolding strategies ("strategies that offer support to students as they learn, including instructional scaffolding, support/guidance, and adaptive, peer-, resource-scaffolding," ibid. p.10) as an intervention approach to enhance CT in the context of ER. Among these, Atmazidou and Demetriadis (2016) used two different forms of guidance in their study: on the one hand, the teacher acting as a facilitator to scaffold students' actions while solving the programming tasks; on the other hand, worksheets guiding students in their investigation of increasingly complex programming tasks. The authors claim that such worksheets enable students "to start constructing understanding and developing the CT skills" (p. 664). In another study, Atmatzidou et al. (2018) compared the effect of two modes of guidance (minimal versus strong guidance) on the development of students' metacognitive (MC) and problem-solving (PS) skills in the context of ER activities. They found out that strong guidance in solving problems can positively impact students' MC and PS skills. This is consistent with the findings of Chevalier and Giang et al. (2020). They explored the effect of timed guidance in an ER learning activity and found that "a scheduled blocking of the programming interface helped foster cognitive processes related to problem understanding, idea generation, and solution formulation" (p.16), which are directly linked to the "computational perspective" dimension of CT. While timed guidance had a clear impact on learning, the intervention did not adapt to each group's progress as it was imposed on all groups without differentiation. In their review, Honomichl and Chen (2012) point out three elements that facilitate guided discovery learning: (1) strategic presentation of materials, (2) consequential feedback, and (3) probing questions and self-explanations. In this regard, probing questions helps direct students' attention to essential features in situations (Chen & Klahr, 1999).

2.1.5. Problematisation inductor

Despite these previous studies, guidance needed to promote CT in ER is not sufficiently explained in the literature, although it is in other STEM areas. Indeed, from the same worksheet perspective, Fabre and Musquer (2009) recommend that science teachers build what they call "problematisation inductors," aiming at "marking critical features" (Wood et al., 1976, p.98), which is one of the six functions of scaffolding. Such a document provides metacognitive questions on the task to realise, the means available, and how to achieve the mission. By answering these questions, students reflect on the problem and improve their identification of the situation, understanding the problem, and solution modelling. As a result, they may enhance their computational perspective dimension of CT. Therefore, the problematisation-inductor worksheet seems relevant because it is an equivalent and adapted intervention for all groups in a class. Indeed, although evident, one should not forget that teachers do not have the gift of ubiquity.

Consequently, teachers' choice of intervention approach impacts the equitable distribution of their guidance among the students. This is what a recent study shows (Mehrotra et al., 2020) comparing the use of paper-based versus a screen-based interface in ER learning activities. The authors show that when using screen-based (instead of paper-based materials), the teachers spent over half their time with a single group of students. In this context, the use of the screen seems to take up the teacher's attention and thus be a physical barrier to equalising teacher interventions with students. Using a worksheet can help structure and sustain the teachers' scaffolding and become a tool for guidance.

2.2. Feedback as an intervention method to foster CT in ER settings

2.2.1. The purpose of feedback in education

According to Wisniewski, Zierer and Hattie's (2020) meta-analysis on the effects of feedback on student learning, "feedback not only refers to how successfully a skill was performed (knowledge on the result) but also to how a skill is performed (knowledge of performance)" (p.7). Thus, in a formative context, feedback aims to "enhance learning, performance, or both, engendering the formation of accurate, targeted conceptualisations and skills" (Shute, 2008) by conveying information about the following three questions (Hattie & Timperley, 2007): Where am I going? How am I going? Where to next? Such information should make sense to learners (Henderson et al., 2017) so that they can reduce the gap between their actual performance and their desired outcome (Hattie and Timperley, 2007; Bahula & Kay, 2020) according to their context and needs (Evans, 2013).

2.2.2. The robot as a source of feedback

As feedback is inherently socially constructed and contextually situated (Ajjawi & Boud, 2017), in a classroom, this traditionally involves two stakeholders: students and teachers. This feedback can take one of two "directions" (Wisniewski, Zierer and Hattie, 2020): feedback can be given by a teacher to one or many students (and vice versa) or given by a student to another student. However, let us consider feedback "as information provided by an agent (e.g., teacher, peer, book, parent, self, experience) regarding aspects of one's performance or understanding" (Hattie & Timperley, 2007, p.81). This increases the number of stakeholders in the context of technology-enhanced learning environments, increasing the number of feedback directions. In ER activities, feedback can also be provided by the robot (behaviour of the robot that executes the programme), the programming interface (which sends back information concerning the programming), or by a third party (a classmate or the teacher).

When considering the robot itself as a source of feedback, one can consider two sources (Merian & Baumberger, 2007; Patchan & Puranik, 2016). On the one hand, intrinsic feedback comes from the subject's perceptual channels. It is what the performer feels as they execute a skill or performance (physical feel of the movement as it is being performed). On the other hand, extrinsic (or augmented) feedback is provided by external sources, during or after a performance (teacher, timer...). In the context of ER, intrinsic feedback refers to the natural sensory information resulting from the manipulation of the robot. This source is rare in ER (except with haptic solutions, Özgür et al., 2017). Conversely, extrinsic feedback is much more present in ER since it deals with the information provided by the robot or the programming interface as soon as an event triggers an action or an error is made. While extrinsic (or augmented) feedback is beneficial in motivating students, informing them about mistakes to be corrected, and directing their attention to their goal, this may create a dependency on feedback (Schmidt & Lee, 2013).

In sum, while the robot in itself is a source of mainly extrinsic feedback in ER learning activities, researchers nonetheless warn us that not all types of feedback are beneficial to student learning and that feedback must be adapted to the students' needs to promote a mindful reflective process.

2.2.3. Types and channels of feedback with robots

According to Hattie & Timperley (2007), “the type of feedback and the way it is given can be differentially effective” (p.81); it is, therefore, necessary to describe the type of feedback found in ER and the channels at our disposal to convey it. Bakala et al. (2021) identified three kinds of feedback provided by robots linked to the affordance of most educational robots’ actuators which we link back to three channels: sound (auditory), light (visual), and movement (haptic). Information can be transmitted through the visual channel employing LEDs, the observable behaviour of the robot (directly or through video recordings when the robot is not directly accessible by the programmer as in our case), or even its programming interface. Videos are a source of extrinsic feedback which can give information about both the knowledge of result and the knowledge of performance (Merian & Baumberger, 2007; section 2.2.1). To the best of our knowledge, no studies have been conducted on video-based feedback during problem-solving in ER activities. The closest work is in physical education using video recordings as a type of delayed video feedback (combined with oral feedback) to reinforce students’ learning. Indeed, this type of feedback helps amplify their auto-perception capacity (Aranha & Gonçalves, 2012), and thus “construct a more accurate mental representation of the performance” (p.117, Merian & Baumberger, 2007), permitting a better regulation of their action and accelerating performance improvement. Nevertheless, these authors recall that too much feedback can lead to a decrease in long-term performance (Magill, 1993; Swinnen, 1996) because “the learner who receives feedback after each trial no longer bothers to engage his or her perceptual system and, in the absence of an external source of information, is unable to regulate his or her movements” (p.109). As a consequence, the frequency and timing of feedback should be taken into consideration.

2.2.4. The timing of feedback

Hattie and Timperley (2007) noted the importance of the information provided during feedback and the appropriateness of the feedback’s timing concerning the students’ instructional cycle. That is why in ER learning activities, the timing of feedback also plays an important role. Observing the robots’ behaviour provides immediate feedback (Papert, 1980) on the program’s quality and concept reification. This feedback elicits the debugging process and triggers “an iterative cycle of observation, hypothesis generation, hypothesis testing and evaluation of the solution” (Sullivan, 2008, p. 389). Students, however, may enter into a trial-and-error strategy (Weintrop and Wilensky, 2015) which is dependent on the status granted to error as a fault or as something to overcome. Teachers may thus choose to give either immediate or delayed feedback by considering the impact of each.

Immediate feedback generates more rapid problem solving (Smith & Lipnevich, 2018; Wise & O’Neill, 2009; Shute, 2008; Hattie & Timperley, 2007) and appears adapted to short and procedural skills (such as programming and maths) by making an explicit association between outcomes and their causes but may generate a type of dependency towards the feedback and promote less careful and less mindful behaviour (Shute, 2008). Indeed, Siegfried et al. (2017) investigated the role of immediate feedback on students’ learning when programming a maze navigation task for a robot. As a result of providing real-time feedback and hints on the code’s performances in the maze, the students were able to quickly solve the task without the intervention of an expert, significantly improved their program writing (from 50 % to 96 %) and decreased the average time to write a correct program by 30%. However, no correlation was found between student learning and performance on the task.

Delayed feedback, on the other hand, generates better retention and transfer in the long term (Smith & Lipnevich, 2018; Wise & O’Neill, 2009; Shute, 2008; Hattie & Timperley, 2007) by engaging learners “in active cognitive and metacognitive processing, thus engendering a sense of autonomy” but may be inadequate for less motivated learners who find themselves frustrated and thus less likely to acquire the desired knowledge or skill set (Schute, 2008). Chevalier and Giang et al. (2020) studied the impact of delayed feedback in creative computational problem solving (CCPS). To break the unproductive trial-and-error loop, access to programming was blocked in certain project phases, thus breaking the access to the immediate feedback on the program's quality. This enabled students to work iteratively on all other cognitive processes of the CCPS model (i.e., Understanding – Generating Ideas – Formulating behaviours). Nevertheless, a more natural blocking access to programming and evaluating through delayed feedback could make the trial-and-error strategy more productive and commensurate with the progress of each pair of students (Lye & Koh, 2014). To the best of our knowledge, there is no research employing delayed feedback in ER to promote CT.

3. Methods and Instruments

To better understand the implementation of our study, in section 3.1, we present the experimental setup of the collaborative remote ER programming mission, which integrates the proposed intervention methods (guidance vs feedback). Then, in section 3.2, we explain the design of the experiment. Subsequently, in section 3.3, we describe the participants and, in section 3.4, the data collection we carried out to capture the students' CT competence, i.e., both their performance and their strategies in creative computational problem solving (CCPS).

3.1. Experimental setup

For this study, we have implemented a modified version of the collaborative remote programming mission R2T2[11] (Mondada et al., 2016) that uses Thymio robots (Papadakis, 2020, p.45; Mondada et al., 2017). Thymio is an open-source mobile robot with generic sensors and actuators. The adaptations limit the mission time to 45 minutes (compared to 3 hours for the regular mission) to suit a real classroom situation.

The mission's goal was to repair an imaginary energy generator on planet Mars (see the upper part of Fig.1, with orange background and zoom on sector C). The task consisted of taking the robots, aligned in front of the external wall of the station, to the access windows of the core generator (central area of the map, point 3 in Fig.1) via the black track (point 2). In the description of the task, the access to the track (point 1) is neither explained nor even mentioned: the students thus had to study the setup, understand the starting situation of their robot, and find a solution how to reach and then follow the track. This mission has to be performed from Earth (see the bottom part of Fig.1, with blue background), where each of the four classes has four computers, each one controlling one robot in the sector corresponding to the class. The Mars setup is situated physically in a distant room, connected by the Internet. This distant room is equipped with a camera allowing visual feedback to the students in their classrooms.

To understand and complete the mission, the students could benefit from a collaborative environment (in teams of 2 or 3 students) and different artefacts (a remote robot and a local one, paper tracks, the video feedback of the setup and their remote robot, and a programming interface). Students had to mobilise their knowledge about the robot's sensors and actuators and then develop an autonomous control strategy to achieve the mission. Their solution was then programmed using the visual programming language Thymio VPL (Shin et al., 2014) and sent to the station's robot (Fig.8). Moreover, students could use local Thymio robots to test their solutions.

[11] https://r2t2-collaboration.com/mars-r2t2-mission/

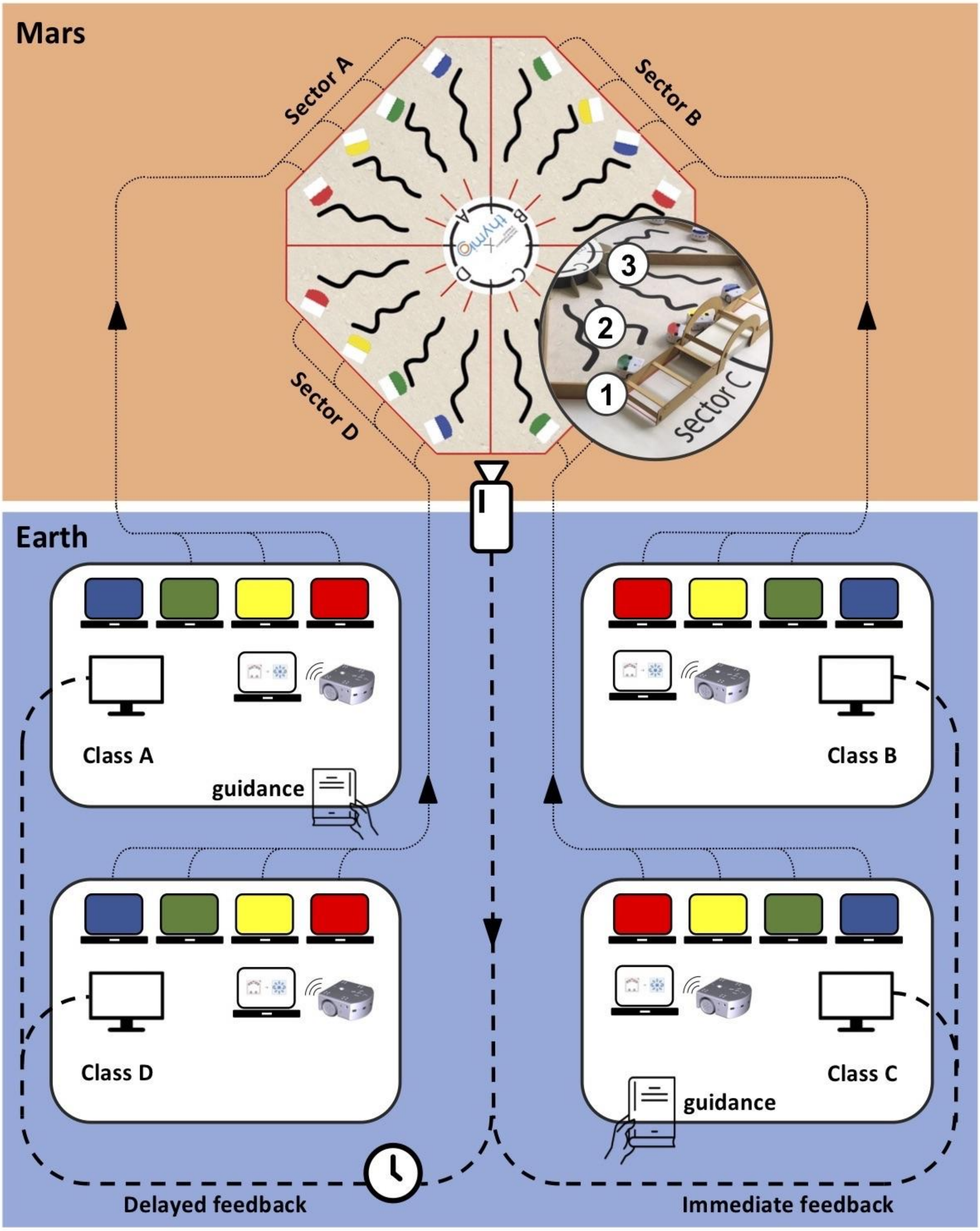

Figure 1: Organisation of the experiment. In the orange background part, labelled "Mars", one physical setup located in a remote office space (standing for the energy generator on planet Mars) consists of 4 quarters (called sectors A, B, C, and D). In each of them, 4 distinct Thymio robots (blue, red, yellow, and green) can be remotely programmed. In the same room, a video camera streams the top view of the four sectors. In the blue part, labelled "Earth", the video streams (see the arrows in lines) are broadcast to 4 classrooms either with a 30-second delay, see classes A and D, or see classes B and C without delay. In each classroom, the participants are subject to 1 of the 4 different experimental conditions: class A is with *guidance* and with *delayed* feedback, class B is without *guidance* and with *immediate* feedback, class C is with *guidance* and with *immediate* feedback, class D is without *guidance* and with *delayed* feedback. In each classroom, each of the 4 pairs of students has the following at its disposal: a Thymio robot to carry out tests locally and a computer on which 3 applications are open (one to record the students' activity on the computer, Thymio Aseba VPL to locally program the robot, and Thymio VPL to remotely program the robot assigned to the team).

3.2. Design of experiment

We set up an experiment with the four possible experimental conditions to identify which of the two selected methods (*with/without guidance* and *immediate/delayed feedback*) fosters the CT dimensions (Table 1). We thus created four groups (classes A, B, C, D) in which we randomly assigned students. For instance, in class A, students were subjected to the experimental condition "*with guidance* and *with delayed feedback*" (Table 1). *Guidance* refers to using a worksheet during the mission, guiding students in solving the mission through metacognitive questions (Appendix C). *Delayed feedback* refers to the video feedback from the energy generator on planet Mars with a delay of 30 seconds which is inherent to the R2T2 Mission[12]. *Immediate feedback* refers to video feedback without delay between the moment students would push the "RUN" button (Fig.8) to send their program to their robot and the moment they would get the video feedback of their robot executing the program on the energy generator on planet Mars. The teacher announced the delay of classes A and D at the beginning of the mission. Moreover, the mission's storytelling justified this delay since the transmission occurs between Earth and Mars (section 3.1).

	Guidance	No Guidance
Immediate Feedback	C	B
Delayed Feedback	A	D

Table 1: Four experimental conditions corresponding to the two modalities with two levels chosen for the "pedagogical intervention" factor and their mapping to the four classes A to D.

Before the mission was carried out, we ensured that the students had the necessary prior knowledge regarding the robot's use and programming. The same person taught a science class 1 hour a week for 12 weeks in each of the four classrooms (Fig.2).

The data were collected using an individual written questionnaire (section 3.4.1) given in 2 stages: before the experiment (pre-test) and after the experiment (post-test). Video data (section 3.4.2) were collected during the experiment, i.e., the collaborative remote programming mission. The experiment was a collective process, as students solved the mission in groups of two or three people.

Figure 2: Research process and dedicated learning time.

[12] https://r2t2-collaboration.com/mars-r2t2-mission/

3.3. Participants

Four classes from two different schools in the Swiss Canton of Vaud participated in the mission, with 66 students (33 girls, 33 boys) aged 8 to 9. Authorisation for the participation of each student was granted by their legal guardians (parents). The school directors and the teachers approved the research. A statement on ethics approval and consent was issued by the Coordination Committee for Educational Research in the Canton of Vaud (Switzerland).

The experiment was carried out twice, once in each school. Each time, two classes were divided into 16 independent groups of 2-3 children, dispatched in 4 different classes, related to 4 different sectors in the playground (Fig.1). Based on an estimation of the students' level that the teacher provided, the students were randomly stratified to ensure a fair distribution of the "educational level" across groups and thus get a homogeneous repartition between conditions (Table 2).

Dimension	Sector A	Sector B	Sector C	Sector D
Level 1 (highest performers)	5	5	4	4
Level 2	4	5	4	5
Level 3	4	4	4	4
Level 4 (lowest performers)	3	3	4	4

Table 2: Number of students per sector having participated in the experiments according to a ranking of their performance in school as provided by the teachers.

3.4. Data collection: A two-step strategy to answer the research questions

The first step was to determine whether there was a significant difference between the four experimental conditions (Table 1). If one (or more) of them were identified, then the second step would be to conduct detailed video analysis of what was going on under the one (or many) experimental conditions(s) that was (or were) favourable.

3.4.1. Measuring CT performance

From state of the art and to have a CT definition with finer granularity compared to the 3 CT dimensions in Brennan & Resnick's model (2012), we selected the six components of the CT competence of Romero et al. (2017) framework (Table 3). We operationalised it into 18 questions (see Appendices A & B) to measure each CT dimension with six questions varied three times. The range was thus 0 to 18 points which we normalise to have a score between 0 (minimum) and 1 (maximum).

CT Dimensions of Brenan & Resnick's model (2012)	CT Dimensions of Romero et al.'s model (2017)	Component of Romero et al.'s model (2017)	Competency component	Questions in our 2 MCQs
Computational Perspective	Analysis	CT1	Problem identification	1, 2, 14
		CT2	Organising and modelling the situation	5, 15, 18
Computational Concepts	Technological literacy	CT3	Code literacy	4, 7, 8
		CT4	Technological system literacy	3, 16, 17
Computational Practices	Making digital creation	CT5	Create a computer program	11, 12, 13
		CT6	Evaluations and iterative improvement	6, 9, 10

Table 3: The 3 CT dimensions, according to Brennan and Resnick (2012), are put face to face with the 3 CT dimensions according to Romero et al. (2017). This face-to-face setting of the 2 models makes it possible to release a finer granularity of the CT (into 6 components) and thus to make it operational into 18 questions.

To avoid measurement reactivity (Van der Maren, 2014, p.113), two different sets of 18 questions (MCQ A and B, Appendices A and B), including the same difficulty of questions, were developed. For the pre-test, the questionnaires MCQ A and B were randomly but equally distributed among the students. The two questionnaires for data collection (MCQ A (μ=0.62±0.13) and MCQ B (μ=0.56±0.15)) are assumed to be equivalent as there was no statistically significant difference between them ($t = 1.35$, $df = 66$, $p > .05$). For the post-test, each participant completed the complementary questionnaire. Subsequently, each answer was graded with either 0 (wrong), 0.5 (partly correct), or 1 point (correct). We then summed the scores for each answer to compute the resulting score for each of the six components (COMP1 to COMP6) and the three corresponding dimensions ("Analysis", "Technological literacy", and "Making digital creation"). As the goal is to observe the learning gain in students' CT scores, we computed the normalised change (NC), a differential score, for each participant, representing the difference between the pre-test and the post-test. Our calculation was based on Coletta and Steinert (2020) 's formula, which consists in:

$$NC = \begin{cases} \frac{Posttest - Pretest}{100\% - Pretest} & if\ Posttest > Pretest \\ \frac{Posttest - Pretest}{Pretest} & if\ Posttest < Pretest \end{cases}$$

Participants who obtained a score of 100% in both pre and post-test ($n = 2$) are not included in the analyses because they are considered unaffected by the experiment.

We first performed a multivariate analysis of variance (MANOVA) on the three dimensions ("Analysis", "Technological literacy", and "Making digital creation") to check for associations between our measures (CT dimensions), factors (*Feedback* and *Guidance*) and their interactions. Then, three independent ANOVA followed on each dimension.

3.4.2. Measuring CT strategies through video analysis

In this second step, we attempted to identify the students' strategies throughout the mission. The qualitative instrument used was videos and screencasts observations. During the collaborative remote programming mission, we recorded the students' activity thanks to a screen recording software, such as

QuickTime Player (Apple, Cupertino, USA), which allows recording students' conversations and making a screencast of their VPL programming. Cameras located in each classroom allowed to record all pairs of students in the classrooms.

To trace the ongoing cognitive processes from the student's activity, we used the existing categories of the CCPS model (Chevalier & Giang et al., 2020; Chevalier and El-Hamamsy et al., 2021; Fig.3), which we evaluated according to the following categories (with indicators as an example): Understanding the problem (USTD, student questions what to do or debug), generating ideas (IDEA, students exclaims that he/she found or knows; offers ideas), formulating the robot behaviour (FORM, the student expresses how should act the robot), programming (PROG, student codes the behaviour of the robot), evaluating (student push the RUN button and observe the robot or video feedback screen), none (student is no longer on the task), and the direction of the gaze (at the VPL screen, the video feedback screen, robot, other groups). In addition to these indicators of the CCPS model, we deepened the "programming" dimension (PROG) to specify it more precisely: how many RUNs? Stop? Locally or remotely? Are there any corrections to the program or even its deletion? (Appendix D). An example of how the judgment was made is given in section 4.2.

Following the same video analysis method explained in Chevalier and Giang et al. (2020, p. 10), one evaluator carried out the video analysis using software dedicated to creating activity chronicles (such as Actograph, developed by SymAlgo Technologies, Paris, France). Student verbatim was also collected and used in the discussion to support the annotations.

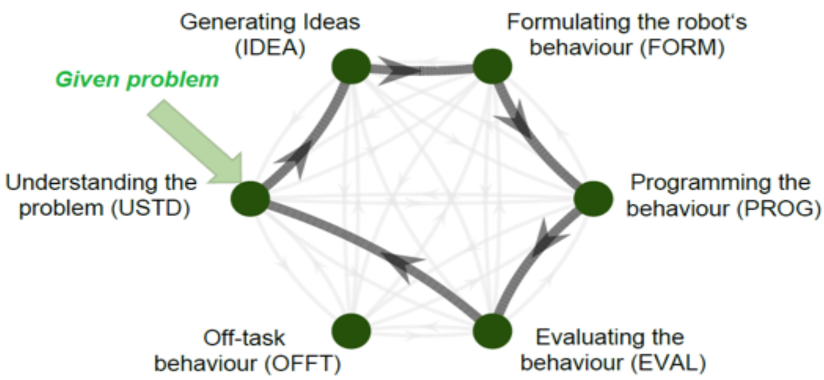

Figure 3: The 6 states of the CCPS model (Chevalier & Giang et al., 2020).

4. Results and discussion

To better answer our two research questions, results and discussion are jointly articulated. Firstly, to answer RQ1, we present the impact of the experimental conditions on CT performance (section 4.1). Subsequently, to answer RQ2, we present the results of the analysis of student strategies according to the experimental conditions found to be significant in RQ1 (section 4.2).

4.1. Between guidance and feedback, which of these two intervention methods most favourably fosters CT competence for 8-9-year-old students? (RQ1)

The distribution of the students' pre and post-test scores is given in Table 4, and both follow a normal distribution according to Kernel density estimation. The results show that students from sectors A and D which both had *delayed feedback* significantly improved their results scores ($t_A(15) = -2.628$, $p_A = .019$, Cohen's $d = 0.68$; $t_D(16) = -4.381$, $p_D = .000$, Cohen's $d=0.94$ with a confidence interval to 95%), with the latter obtained the best average scores in the post-test ($\mu_D=0.68\pm0.08$). Only the group from sector B (*immediate feedback*, *no guidance*, as experimental conditions) remained on the same level between these two measurements (pre-test, μ=0.67±0.10; and post-test μ=0.66±0.15). This result is consistent with the low effectiveness of minimal *guidance* shown in the literature (Kirschner et al., 2006). However, sector D, subject to *delayed feedback without guidance*, has the highest post-test score. Thus, it seems that the combination of *guidance* and *feedback* methods might have affected student CT performance differently.

Sector	Experimental conditions	Time	Analysis	Technological Literacy	Making Digital Creation	Total Mean CT Score	Mean CT Score Improvement Significance
A	Guidance	Pre-test	0.61 ± 0.19	0.69 ± 0.15	0.40 ± 0.21	0.57 ± 0.15	***t*(15) = -2.628, p = .019, Cohen's d = 0.68**
	Delayed Feedback	Post-test	0.63 ± 0.16	0.84 ± 0.18	0.50 ± 0.24	0.66 ± 0.17	
B	No Guidance	Pre-test	0.66 ± 0.18	0.76 ± 0.10	0.57 ± 0.25	0.67 ± 0.10	*t*(16) = .118, p = .907
	Immediate Feedback	Post-test	0.59 ± 0.13	0.84 ± 0.11	0.55 ± 0.23	0.66 ± 0.15	
C	Guidance	Pre-test	0.60 ± 0.16	0.65 ± 0.21	0.44 ± 0.30	0.56 ± 0.11	*t*(15) = -1.115, p = .282
	Immediate Feedback	Post-test	0.69 ± 0.17	0.67 ± 0.19	0.49 ± 0.20	0.62 ± 0.11	
D	No Guidance	Pre-test	0.63 ± 0.20	0.59 ± 0.21	0.44 ± 0.21	0.55 ± 0.10	***t*(16) = -4.381, p = .000, Cohen's d = 0.94**
	Delayed Feedback	Post-test	0.74 ± 0.16	0.72 ± 0.16	0.59 ± 0.28	0.68 ± 0.08	

Table 4: Distribution (Mean μ, SD σ) of students' pre and post-test scores per sector. In bold are the significant changes in performance.

Based on the normalised change (NC, section 3.4.1) in Table 5, the multivariate analysis of variance (MANOVA) on the 3 CT dimensions allows us to identify an interaction effect between *feedback* and *guidance* (F(3, 60) = 2.772, p = 0.049). We then performed a one-way ANOVA on each CT dimension. As shown in Fig.4, results for the "Analysis" dimension highlight a significant interaction between *feedback* and *guidance* (F(1, 62)= 5.32, p = 0.024), i.e. the effect of *feedback* seems to differ according to the *guidance*: when there is *no guidance*, then *delayed feedback* is relevant for learning. No other significant effects were found for the "Analysis" dimension, the "Technological literacy" dimension and the "Making digital creation" dimension.

Dimension	Observations	Min./Max.	Mean / SD
Analysis	66	-0.55 / 1.00	0.13 ± 0.41
Technological Literacy	66	-0.60 / 1.00	0.32 ± 0.46
Making Digital Creation	66	-1.00 / 0.83	0.10 ± 0.46

Table 5: Distribution of students' Normalised Change scores per dimension (Mean μ, SD σ, min and max values).

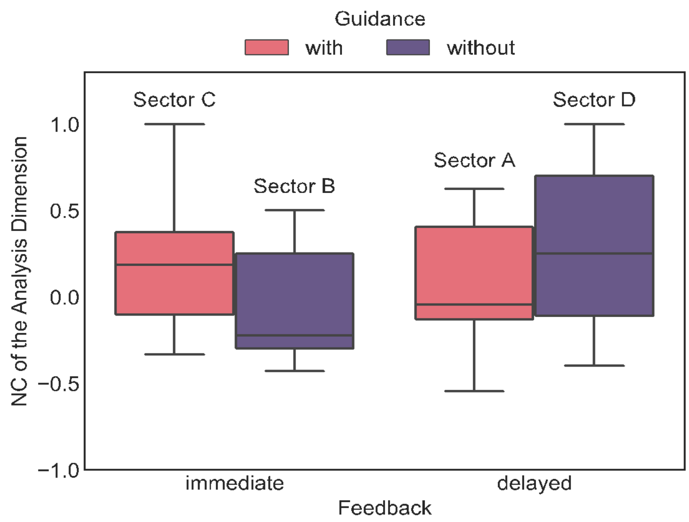

Figure 4: Boxplots of CT Normalised Change (NC) on the "Analysis" dimension of CT (Romero et al., 2017) according to *Feedback* (delayed/immediate) and *Guidance* (with/without). Letters A, B, C, D indicate the sector in the experiment. The dark line indicates the NC median.

At this stage, our results show that *delayed feedback* significantly fosters the "Analysis" dimension of CT, provided *no guidance* is given. We thus propose to consider *delayed feedback* as an effective intervention method for CT development in ER activities, thus addressing the lack of a specific intervention approach raised by Lye and Koh (2014). As only one guidance approach was tested, more research is required to investigate the impact of specific guidance methods.

4.2. How does feedback impact students' problem-solving strategies? (RQ2)

To further develop these results, we analysed the videos to investigate the relationship between the mobilised competences and learning among the students that were only subjected to *feedback* (immediate or delayed), i.e., in sectors B and D, which incidentally differ quite significantly (at 10% threshold) in terms of their normalised change ($t(32) = -2.392$, $p = 0.086$, Cohen's $d = 0.82$) for the "Analysis" dimension of CT.

The aim is to evaluate the students' learning strategies and thus to understand how they construct meaning in interaction with the playground (Chevalier & Giang et al., 2020) and in dialogue with each other (Denner et al., 2014) to investigate the reason behind these differences. Results from the analysis of 4 groups from sector D (9 students, 794 CCPS transitions in total) and 4 groups from sector B (10 students, 596 CCPS transitions in total) are presented in Figure 5. As shown in Table 6, students in sector B completed the mission almost 3 times faster than those in sector D. On average, students in sector B performed almost twice as many transitions per minute than in sector D. Under immediate feedback, a "doing" based strategy (Lye & Koh, 2014) seems to be prevalent, as opposed to delayed feedback which seems to favour "thinking-doing" (ibid).

Moreover, students in sector B engaged faster in remote programming than those in sector D. As shown in Figure 6, behaviours differ between the two experimental conditions in sectors B and D, which may explain the different NC scores between them. The students working with the *immediate feedback* (sector B) are more likely to transition into a nearly endless PROG-EVAL loop (see two-way arrows in Fig.6): on average, under *immediate feedback* and from the PROG phase, students have a 70% chance of moving toward the EVAL phase (and 78% from EVAL to PROG). Comparably, the students subjected to the *delayed feedback* (sector D) do not get stuck into this same loop as they also promote other mental activities (see the one-way arrow between EVAL and USTD phases in Fig.6). Moreover, time spent on PROG and especially on EVAL phases is more substantial under the *delayed feedback* than *immediate feedback* (see the diameter of the blue dots in Fig.6). This point can be justified in part considering the 30 seconds *delayed feedback*.

Nevertheless, on average, only students in sector D complete a full CCPS cycle (USTD-IDEA-FORM-PROG-EVAL). They, therefore, have a greater chance of developing the targeted CT competences. It is thus relevant to identify in the videos, thanks to students' verbalisations (Denner et al., 2014), what this type of *feedback* implies in the students' strategies.

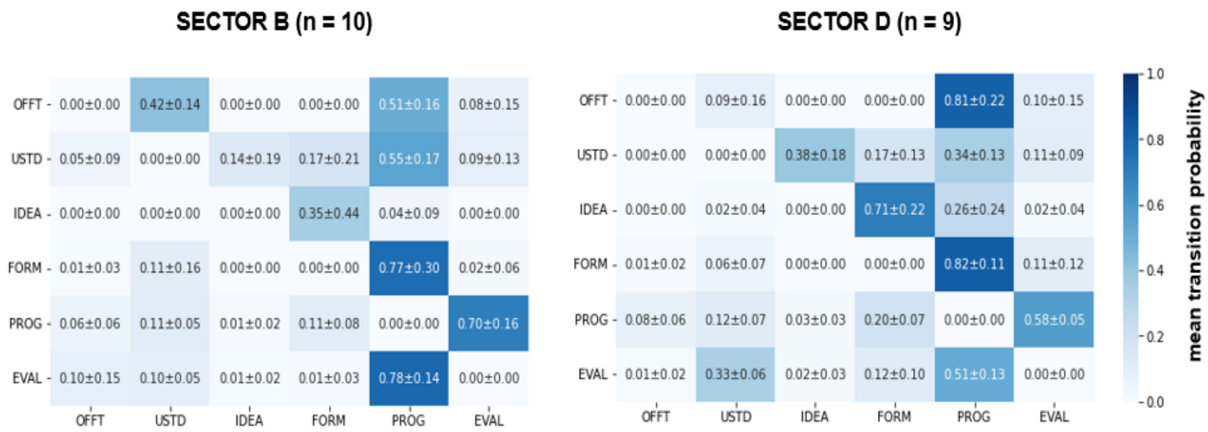

Figure 5 - Distribution (Mean μ, SD σ) of the normalised transition matrices for both sectors B and D. The colour of the boxes varies from lightest to darkest (from 0 to 1).

Average number of transitions:	**Sector B**	**Sector D**
- **during the entire mission**	59.10 ± 19.85	88.22 ± 37.40
- **per minute**	4.97 ± 1.11	2.88 ± 0.40
Average time in minutes:		
- **to complete the mission**	11.91 ± 3.17	32.22 ± 15.01
- **before the 1st remotely-RUN**	5.67 ± 3.65	8.03 ± 6.85

Table 6: Average (Mean μ, SD σ) of transitions and time during the mission in sectors B and D.

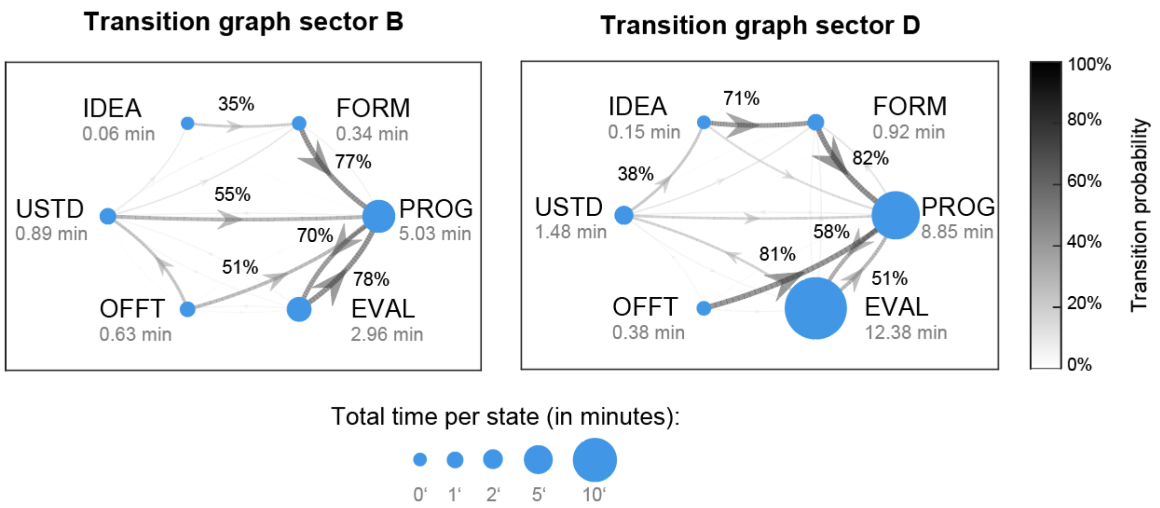

Figure 6 - CT strategies analysis between sectors B and D during the mission. The 6 CT processes (according to the CCPS model, Chevalier & Giang et al., 2020) are Understanding (UND), Generating idea (IDEA), Formulating the robot behaviour (FORM), Programming (PROG), Evaluating (EVAL), out of the task (OFFT). The thickness of the line shows the transition probability. The diameter is directly proportional to the duration. Note that students in sector D tended to spend more time doing the mission.

As shown in figure 5, the means for groups B and D are different, but they seem consistent since the SD values are neither large nor variable. Among the mean differences, nine significant differences have been identified and highlighted in figure 7 (see the coloured boxes). We present them as follows and will discuss them in sections 4.2.1 and 4.2.2.

Compared to students in sector D, students in sector B (submitted to immediate feedback) were more significantly likely to move from the USTD to PROG phase ($p = 0.012$), i.e., once they have identified the problem or the bug, they program directly. In addition, they were more significantly likely to move backwards from the EVAL to PROG phase ($p = 0.002$), suggesting a more behavioural than cognitive process. Finally, they were more significantly likely to move from the EVAL to FORM phase (($p = 0.006$), suggesting that they negotiated the behaviour of the robot to be programmed while evaluating the current programmed behaviour.

Compared to students in sector B, students in sector D (submitted to delayed feedback) were more significantly likely to move from the EVAL toward USTD phase ($p = 0.000$), suggesting a debugging strategy, and then from the USTD toward IDEA phase ($p = 0.018$). They were more significantly likely to move from the IDEA toward PROG phase ($p = 0.026$), skipping the FORM phase momentarily to better return to it from the PROG to FORM phase ($p = 0.041$), suggesting that the delay represents a cost of waiting students do not necessarily wish to pay (and thus they prefer to formulate the behaviour again to be programmed without executing the code). Finally, they were more significantly likely to move from the FORM toward EVAL phase ($p = 0.024$), representing what happens in the wait caused by the delay (after reformulating the behaviour to be programmed that they have just programmed, they execute the code to evaluate it).

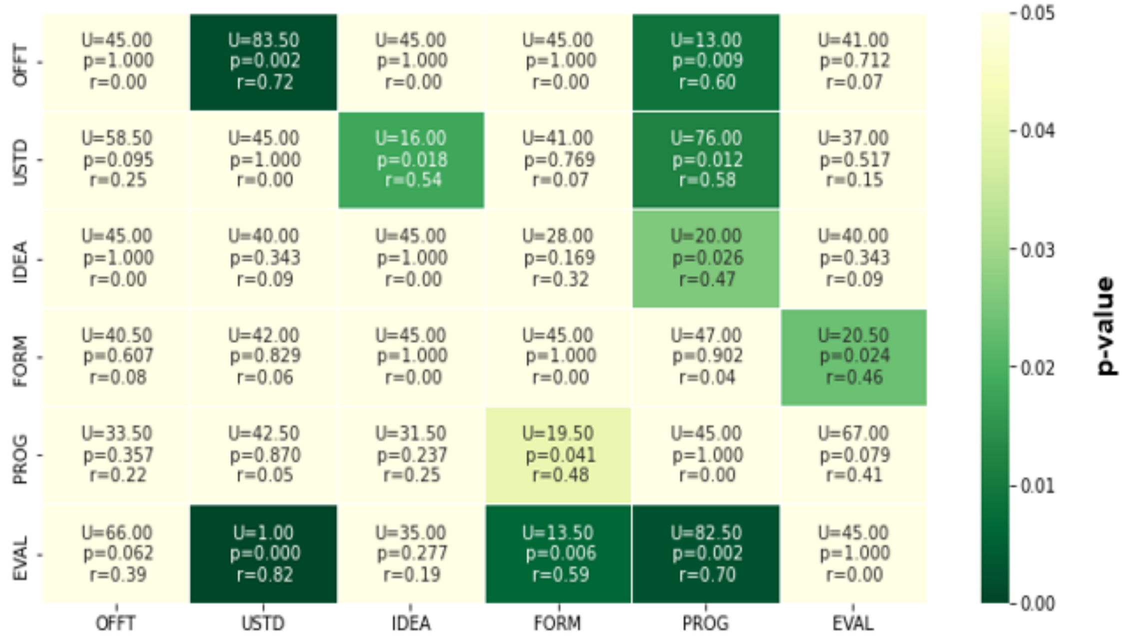

Figure 7 - Significant differences between the transition matrices of groups B and D. The boxes' colour varies from green to yellow, indicating a risk threshold from 1% to 5% (Mann-Whitney U-test).

4.2.1. The effect of Immediate Feedback on students' problem-solving strategies

The students in sector B (with *immediate feedback* and *no guidance* as an experimental condition) mainly adopted a programming and evaluating strategy (Fig.5 & 6). This is a usual behaviour in ER (Chevalier & Giang et al., 2020) which refers to a "trial-and-error" strategy (Weintrop & Wilensky, 2015), i.e. a problem-solving method in which multiple attempts are made to reach a solution. They accomplished the task more quickly (Siegfried et al., 2017; Mayer, 2004; Biesta & Burbules, 2003) but to the detriment of developing all the cognitive processes necessary in CT (Chevalier & Giang et al., 2020). The *immediate feedback* makes it possible to act and react quickly (Smith & Lipnevich, 2018; Wise & O'Neill, 2009; Shute, 2008; Hattie & Timperley, 2007). Nevertheless, productive trial-and-error should bring "an iterative cycle of observation, hypothesis generation, hypothesis testing and evaluation of the solution" (Sullivan, 2008, p.389). However, as highlighted in Fig.6, there is little formulation (FORM) before programming, and therefore few hypotheses are generated. The trial-and-error strategy focuses on the action exerted directly on the robot rather than on evaluating the program's syntax that controls the robot's behaviour. This suggests little student anticipation whose PROG and EVAL phases are essentially dedicated to using the robot like a remote-controlled car. Thus, the students subjected to *immediate feedback* are in the immediacy of the action, which leads to a more reactive strategy, as opposed to the more deliberative strategy of those with *delayed feedback* (section 4.2.2). Moreover, immediate feedback generates a dependency on feedback (Schmidt & Lee, 2013). Students with *immediate feedback* start on average 5 minutes (Table 6) after the start of the mission to instrument both RUN and STOP buttons (Fig.8) with minimalist programs to control their robot remotely. Consequently, the trial-and-error strategy (PROG-EVAL) seems to be due to this instrumentation to remotely control the robot (Rabardel, 1995) and a lack of agreement on formulating the robot behaviour before the execution. Indeed, in sector B, the students express very little agreement among themselves, and their verbalisations remain at the level of observation ("Oh no, he didn't turn...", "Yes, he made it!"). It seems that, in a remote collaborative robot programming mission, *immediate feedback* decreases group communication in favour of action: this leads to trial-and-error-based problem-solving strategies for 8-9-year-old students.

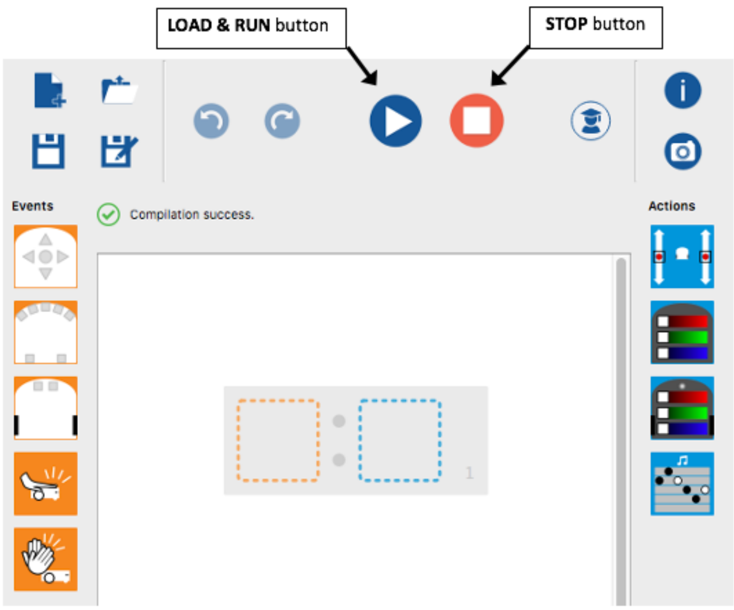

Figure 8 - The visual programming language Thymio VPL (Shin, Siegwart, & Magnenat, 2014) with the RUN button to upload the program on the robot and execute it, and the STOP button to stop the execution of the program.

4.2.2. The effect of Delayed Feedback on students' problem-solving strategies

The students in sector D (with *delayed feedback* as an experimental condition) mainly adopted a programming and evaluation strategy (Fig.5 & 6) but with interim transitions towards other phases. Students cannot get into this PROG-EVAL loop as it costs them time (30 sec.) when they click on the RUN button. Indeed, while waiting for the visual *feedback* of the remote execution of their program, students verbalise their incomprehension ("but why isn't he moving?") or anxiety ("Let's hope it works!"). They even anticipate what should be done ("you should move the robot backwards because it might get into the other robot"). Thus, they are going into the path USTD-IDEA-PROG-FORM-EVAL ("it's going to move forward and then it's going to turn around", "Come on, Thymio, do what you've been told to do: move forward and turn before the wall!"). Such a strategy (trial-and-error and reasoned simultaneously) refers to Merisio et al. (2021), who stated it is time and memory consuming.

In sector D, students formulate more and pool their strategy: the delayed *feedback* seems to lead them to (re)negotiate the tasks before pressing the RUN button. As a result, we observe a return to the PROG without even having had the EVAL, hence the FORM-PROG loop (Fig.5). This delay forces the students to give more thought to a larger program's syntax and agree on the program sent. For example, in a group of two students, the frustration of waiting to see the programming result leads the student who programmed to reflect on his program and identify aspects to be improved. This change calls out to the other student, who then demands explanations, and they complete their program together.

Moreover, in the long, the students are also tempted to "remote control" the robot to succeed in the mission by instrumenting the RUN and STOP buttons (Rabardel, 1995). Nevertheless, the delay prevents them from doing so, hence they are forced to proceed to other instruments (including testing with the locally available Thymio robots). Indeed, if the RUN button keeps its function to start the program and thus to evaluate it, the STOP button becomes random: it does not allow to stop the robot properly because of the *delayed feedback*. The decision to "stop" the program is then not taken for granted because it can amplify its potential error that cannot yet be evaluated. Thus, the students are more anticipatory as they are forced to think and verbalise to pool their thoughts. They are forced to anticipate and communicate (Denner et al., 2014) and make a shared decision. As a result, the robotics environment's affordances coupled with the *delayed feedback* may trigger a FORM-PROG loop in addition to the PROG-EVAL loop already identified, resulting in a more productive trial-and-error strategy.

4.2.3. The effect of guidance on problem-solving strategies

Despite a lack of significant results in terms of NC under the "*guidance*" experimental condition (sectors A and C), viewing the videos allows us to identify similar problem-solving strategies. Under *guidance* and *immediate feedback* (sector C), students could better decompose the problem and identify the robot's starting position, i.e., out of the trackline. Nevertheless, the instrumentation of immediate video *feedback* coupled with the VPL's affordances resulted in an unproductive trial-and-error strategy. Concerning sector A, it was *a priori* the most favourable learning conditions as students were subjected to *guidance* and *delayed feedback*. Nevertheless, results do not indicate any particular performance under these experimental conditions. The video viewing allows identifying a strategy close to the one deployed in sector D. Further research is needed to understand better what is at stake in the interaction between *guidance* and *delayed feedback* in sector A. In addition, the 12 hours class before the mission may have made the students experts on the type of tasks proposed during the mission. However, as Clark et al. (2012) noted, expert students can still learn with minimal guidance. As a result, the role of guidance at the beginning of the course, when scaffolding is still needed, should be verified in a future study.

5. CONCLUSION

In this study, we were interested in intervention methods that foster CT competence in the context of ER activities for 8-9-year-old students. Based on the literature, we identified *guidance* (with/without) and *feedback* (immediate/delayed) as two promising intervention methods to foster CT competence in classroom settings, in accordance with teaching practices. After a 12-hour ER course with the Thymio robot, 66 students accomplished a collaborative remote programming mission under four distinct experimental conditions: *with guidance* and *with delayed feedback*; *without guidance* and *with immediate feedback*; *with guidance* and *with immediate feedback*; *without guidance* and *with delayed feedback*. Before and after this mission, pre- and post-tests were carried out, and the results showed the significant positive impact of using *delayed feedback* on the "Analysis" dimension of CT.

Moreover, based on the video recorded during this mission, we observed and evaluated the different strategies implemented under experimental conditions showing a significant difference: the two types of *feedback* (immediate and delayed) do not lead to the same cognitive processes and learning outcomes: each brings a specificity but also has its limits, as it has already been shown in other studies on *feedback* (Smith & Lipnevich, 2018; Wise & O'Neill, 2009; Shute, 2008; Hattie & Timperley, 2007). Indeed, if one seeks to facilitate accomplishing the task or mission, then *immediate feedback* is favourable. However, this does not allow the students to develop more elaborate CT processes such as those described in the computational perspectives and practices dimensions (Brennan & Resnick, 2012). On the other hand, if one seeks to foster deeper CT processes, *delayed feedback* is more favourable. However, care must be taken not to tire and therefore disengage the students throughout the mission with *delayed feedback*. In our case, the delay made sense because it was naturally included in the challenge of having a robot on Mars.

This study addresses the four recommendations of Lye and Koh (2014) by exploring a classroom-based intervention, focusing on computational practices and computational perspectives, examining the programming process, and analysing qualitative data. In particular, our results on *delayed feedback* help address their recommendations regarding fostering the CT's computational perspectives dimension. Consequently, we also address the recommendations of Tikva and Tambouris (2021, p.26) for clarity about factors that may affect CT acquisition.

However, the results about guidance with a worksheet are not significant, although guidance is described in the literature as a factor promoting learning (Kirschner et al., 2006, p.80-81). It seems that there are two limitations to our study. On the one hand, the medium chosen to convey guidance (via metacognitive questions) does not seem relevant to 8-9-year-old students. Perhaps a certain level of self-direction (i.e. taking sole responsibility for one's learning) is necessary to make good use of it. On the other hand, due to our design of experiment, an interaction effect between the effect of guidance and feedback (immediate and delayed) may have occurred. It seems that the guidance modality chosen here (the worksheet) does not offer sufficient incentive to break the "doing" and "think-doing" patterns brought on, respectively, by the trial-and-error appeal offered by immediate feedback and the cognitive load imposed by delayed feedback.

What type of guidance should the teacher provide to encourage student development of CT? The solutions to be explored may be a priori counterintuitive, as shown in this study with delayed feedback (due to the live streaming latency). This leads us to believe that any technical constraint can be perceived as a pedagogical opportunity. Future work should focus on the guidance factor to find an appropriate balance between scaffolding methods and consider the "Help me do it alone" duality raised by Montessori (1973). In addition, future studies should make it possible, on the one hand, to identify the types of errors during a CCPS situation and, on the other hand, to propose the kind of adequate feedback for the student to overcome his errors.

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SUPPLEMENTARY MATERIAL

- MCQ A
- MCQ B
- Worksheet for guidance
- Video analysis protocol

MCQ A

Question 1

Here is a picture of Thymio :  What is happening in this picture?	Circle the answer that seems most accurate to you: a) The robot does not pick up anything in front of it. b) The robot is picking up something in front of it (from all its sensors). c) The robot is picking up something in front of it (thanks to its front sensor).

Question 2

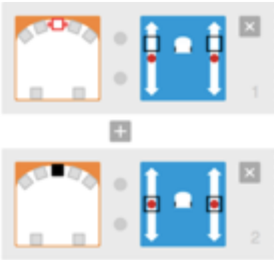
Here is a picture of Thymio :  What is happening in this picture?	Circle the answer that seems most accurate to you: a) The robot does not pick up anything in front of it. b) The robot is picking up something in front of it (from all its sensors). c) The robot is picking up something in front of it (thanks to its front sensor).

Question 3

What is the image that represents when Thymio does not pick up something with its rear sensors?	Circle the answer that seems most accurate: a)  b)  c) 

Question 4

Here is a programme :



What does it mean?

Circle the answer that seems most accurate:

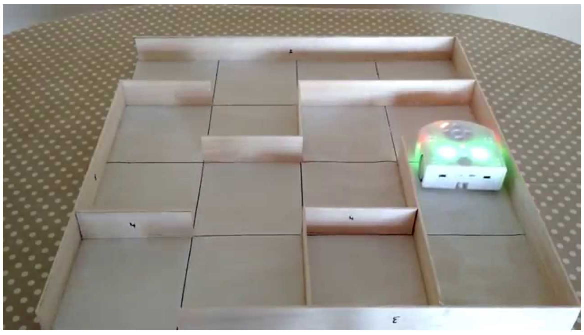
a) If Thymio picks up something in front of it, then it stops its motors; otherwise it moves forward.

b) If Thymio picks up something in front of it, then it moves forward; otherwise it stops its motors.

c) If Thymio picks up something, then it stops its motors or moves forward.

Question 5

Here is a picture of Thymio in a maze:



Explain in your own words what Thymio should do (and how it can do it).

(Start your sentences with 'if'):

……………………………………………………

……………………………………………………

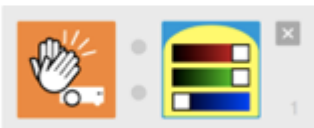
……………………………………………………

……………………………………………………

……………………………………………………

Question 6

Here is a programme :



I clicked on the play button: .

Now, what do you need to do to "test" this program?

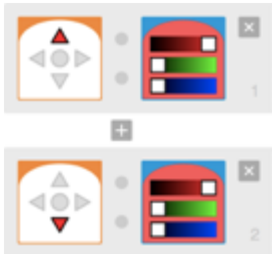
Circle the answer that seems most accurate:

a) You should say "turn on yellow" and check that Thymio turns on yellow.

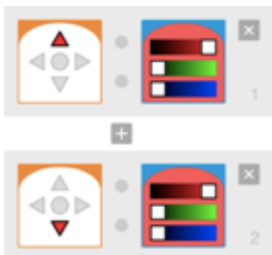
b) Clap your hands and check that Thymio turns yellow.

c) You have to make a noise (clap, whistle, ...) and check that Thymio lights up yellow.

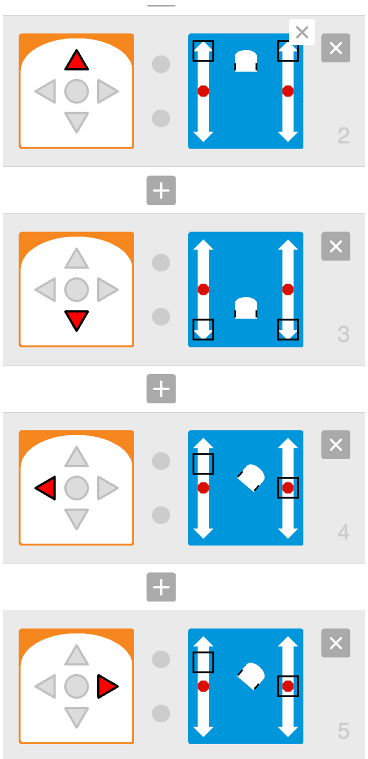
Question 7

I want to program Thymio to light up red when its front AND back buttons are pressed. What is the image that corresponds to this program?	Circle the answer that seems most accurate: a)  b)  c) 

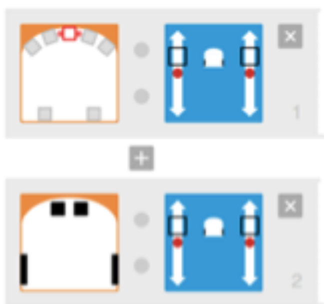
Question 8

I want to program Thymio to light up red when its front OR back buttons are pressed. What is the image that corresponds to this program?	Circle the answer that seems most accurate: a)  b)  c) 

Question 9

Here is a program to make Thymio move using the buttons:  When I tested this program, I encountered a problem! Which one and how can I fix my program?	Circle the line in the program where the error is and write what needs to be fixed: ………………………………………………… ………………………………………………… ………………………………………………… ………………………………………………… ………………………………………………… ………………………………………………… ………………………………………………… ………………………………………………… ………………………………………………… …………………………………………………

Question 10

Here is a programme :  When I tested this program, I encountered a problem: the robot fell off the table! How can I correct my program?	Circle the answer that seems most accurate to you: a) On the 2nd line, you need to correct the blue icon and turn the engines off. b) On the second line, change the orange icon and click on the ground sensors so that they become grey. c) On the second line, change the orange icon and click on the ground sensors so that they become red.

Question 11

Here is a picture of a challenge I would like to do with Thymio:

How do you program Thymio to do this challenge?

Explain here in words how you would program it:

....

....

....

....

Question 12

Here is a picture of a challenge I would like to do with Thymio:

How do you program Thymio to do this challenge?

Explain here in words how you would program it:

....

....

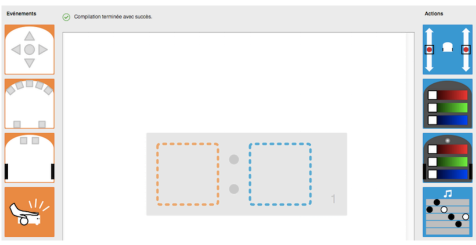
....

....

Question 13

Remember the green mode? It can follow your hand. Now it's up to you to program Thymio to follow you, but with its rear sensors!

As a reminder, here is a picture of the VPL:



To write the program, draw and modify the icons in the column opposite. Be careful to think of all possible situations!

Draw the VPL icons here and modify them if necessary:

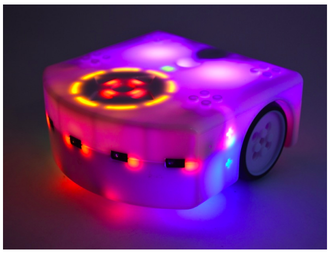
Question 14

Here is a road that crosses a city:  Could Thymio in blue mode follow this route?	Circle the answer that seems most accurate to you: a) Yes, because the road is white. b) No, because the road is white. c) No, because the road has pedestrian crossings and dotted lines.

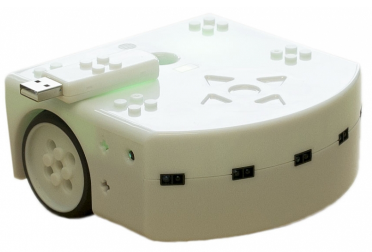
Question 15

I would like to use Thymio to avoid obstacles in a small enclosure measuring 1 metre by 1 metre on the floor. Can you draw a diagram of what Thymio will have to do ?	Make your diagram below:

Question 16

Here is a picture of Thymio:  What is the name of the actuator that allows Thymio to light up in different colours?	Circle the answer that seems most accurate: a) proximity sensors b) LEDs c) motors

Question 17

Here is a picture of Thymio:  What is the purpose of the dongle?	Circle the answer that seems most accurate: a) to transmit the program from the computer to the robot. b) to record information (text, images, photos, etc.). c) to program the robot.

Question 18

Here is a programming challenge with Thymio that you have been asked to complete in 5 minutes:  How do you plan to organise yourself?	Circle the answer that you think is most accurate: a) As I don't know the challenge yet, I think I will try to understand the problem to be solved first before programming Thymio. b) As I don't have much time, I think I will program Thymio directly. c) As I know the basic modes of Thymio (its 6 colours) then I think I will use them.

MCQ B

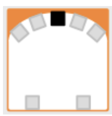
Question 1

Here is a picture of Thymio :  What is happening in this picture?	Circle the answer that seems most accurate: a) The robot does not pick up anything behind it. b) The robot picks up something behind it (thanks to all its sensors). c) The robot picks up something behind it and moves backwards.

Question 2

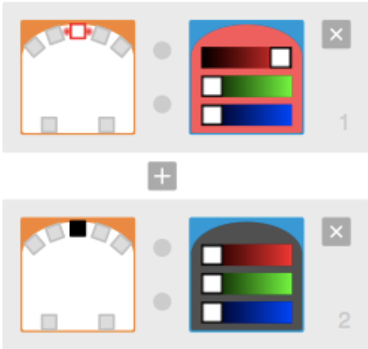
Here is a picture of Thymio :  What is happening in this picture?	Circle the answer that seems most accurate: a) The robot does not pick up anything behind it. b) The robot picks up something behind it (thanks to all its sensors). c) The robot picks up something behind it and moves backwards.

Question 3

What is the image that represents when Thymio does not pick up something with its front sensor?	Circle the answer that seems most accurate:  a)  b)  c)

Question 4

Here is a programme:



What does it mean?

Circle the answer that seems most accurate:

a) If Thymio picks up something in front of it, then it turns on red; otherwise it turns off.

b) If Thymio picks up something in front of it, then it turns off; otherwise it turns on red.

c) If Thymio picks up something, then it turns off or lights up red.

Question 5

Here is a picture of two Thymio (one in green mode and one in yellow mode):

Explain in your own words what the Thymio should do in green mode (and how it can do it).

....

....

....

....

....

Question 6

Here is a programme :

I clicked on the play: button. 

Now, what should I do to "test" this program?

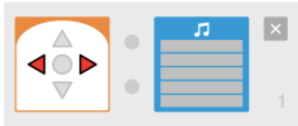
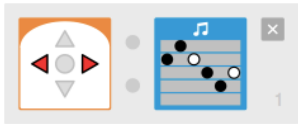
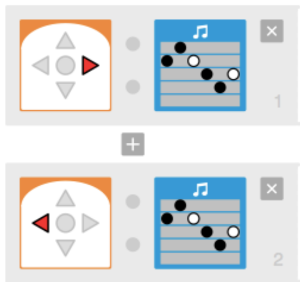
Circle the answer that seems most accurate:

a) You have to say "move forward very hard" and check that Thymio is moving forward.

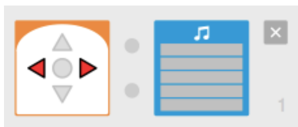
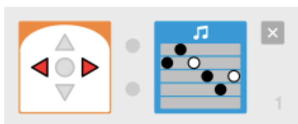
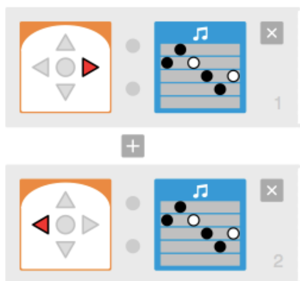
b) Put your hand on Thymio and check that Thymio is moving.

c) Tap Thymio and check that Thymio is moving.

Question 7

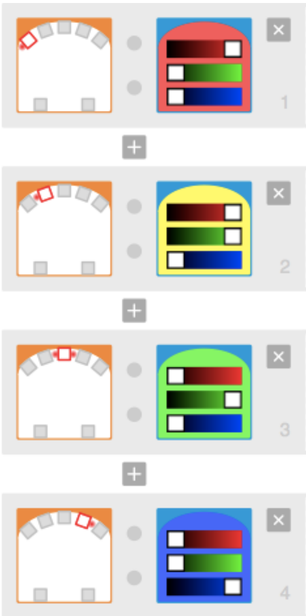
I want to program Thymio to make music when its left **AND** right buttons are pressed. What is the image that corresponds to this program?	Circle the answer that seems most accurate:  c)  d)  c)

Question 8

I want to program Thymio to make music if you press its left **OR** right buttons. What is the image that corresponds to this program?	Circle the answer that seems most accurate:  c)  d)  c)

Question 9

Here is a program that allows Thymio to change colour using its front proximity sensors :



When I tested this program, I had a problem with the sensor on the far right: it did not change colour!

How to correct my program?

Write down what needs to be fixed in this program:

....

....

....

....

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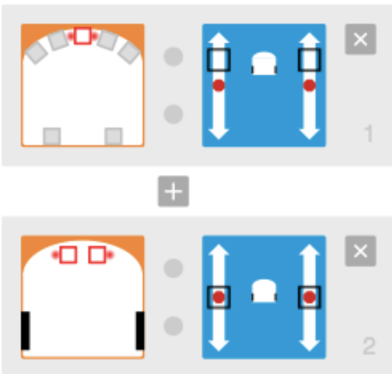
....

Question 10

Here is a programme :



When I tested this program, I encountered a problem: the robot fell off the table!

How can I correct my program?

Circle the answer that seems most accurate to you:

a) On the 2nd line, correct the level of the motors and make them go backwards.

b) On the second line, you have to correct the sensors underneath and put them in black.

c) On the second line, correct the level of the motors and make them go forward.

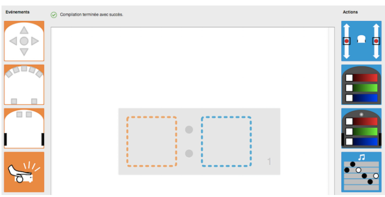
Question 11

Here is a picture of a challenge I would like to do with Thymio :  How do you program Thymio to do this challenge?	Explain here in words how you would program it: …………………………………………………… …………………………………………………… …………………………………………………… ……………………………………………………

Question 12

Here is a picture of a challenge I would like to do with Thymio:  How do you program Thymio to do this challenge?	Explain here in words how you would program it: …………………………………………………… …………………………………………………… …………………………………………………… ……………………………………………………

Question 13

Remember the pink mode? You can move it with its buttons. Now it's your turn to program Thymio to move, but not in the usual way: in the opposite direction! As a reminder, here is a picture of the VPL:  To write the program, draw and modify the icons in the column opposite. Be careful to think of all possible situations!	Draw the VPL icons here and modify them if necessary:

Question 14

Here is a tunnel I built:  Could Thymio in yellow mode get out of this tunnel by itself?	Circle the answer that seems most accurate to you: a) Yes, because in yellow Thymio avoids obstacles. b) No, because the edges of the tunnel could be seen as obstacles for Thymio. c) No, because in yellow Thymio avoids obstacles.

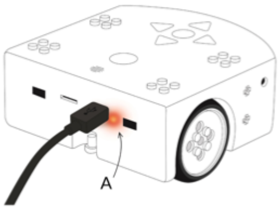
Question 15

I would like to use Thymio to knock down pins (like bowling with 6 pins). Can you draw a diagram of what Thymio will have to do?	Make your diagram below:

Question 16

Here is a picture of Thymio:  It can emit music or sound thanks to the actuator circled in red on the photo: what is its name?	Circle the answer that seems most accurate: a) the LEDs b) the speaker c) the microphone

Question 17

Here is an image of Thymio:  What is the purpose of the black cable?	Circle the answer that seems most accurate: a) to recharge the robot. b) to record the robot's information. c) to program the robot.

Question 18

Here is a programming assignment with Thymio that you have been asked to complete:  How do you plan to organise yourself?	Circle the answer that seems most accurate: a) Since I don't know the mission yet, I think I will try to understand the problem to be solved first. b) As I know a little about the VPL, I think I will program Thymio directly. c) As I know the basic modes of Thymio (its 6 colours), I think I will use them.

Worksheet for guidance

First names : ………………………………………………… N° Team number : ……

R2T2 Mission

Save the Thymio station on Mars!

This is the Thymio station on Mars:

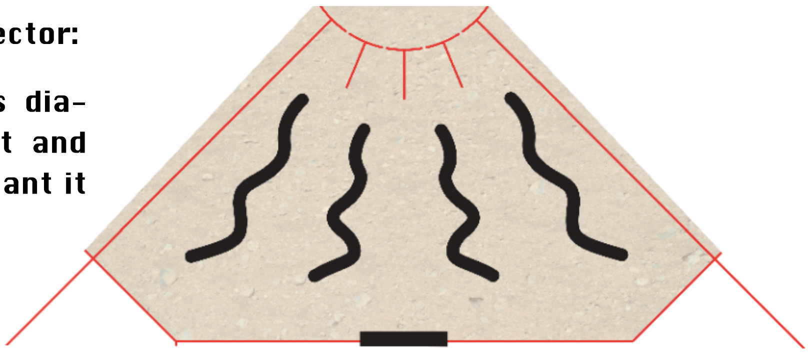
How many sectors do you see? ....

Which sector are you in? ....

What colour is your Thymio in this sector? ....

Here is a diagram of your sector:

Draw your Thymio on this diagram at its starting point and draw a cross where you want it to arrive.



Now think about the path your robot will have to take to get from the starting point to the end point.

Draw this path on the diagram.

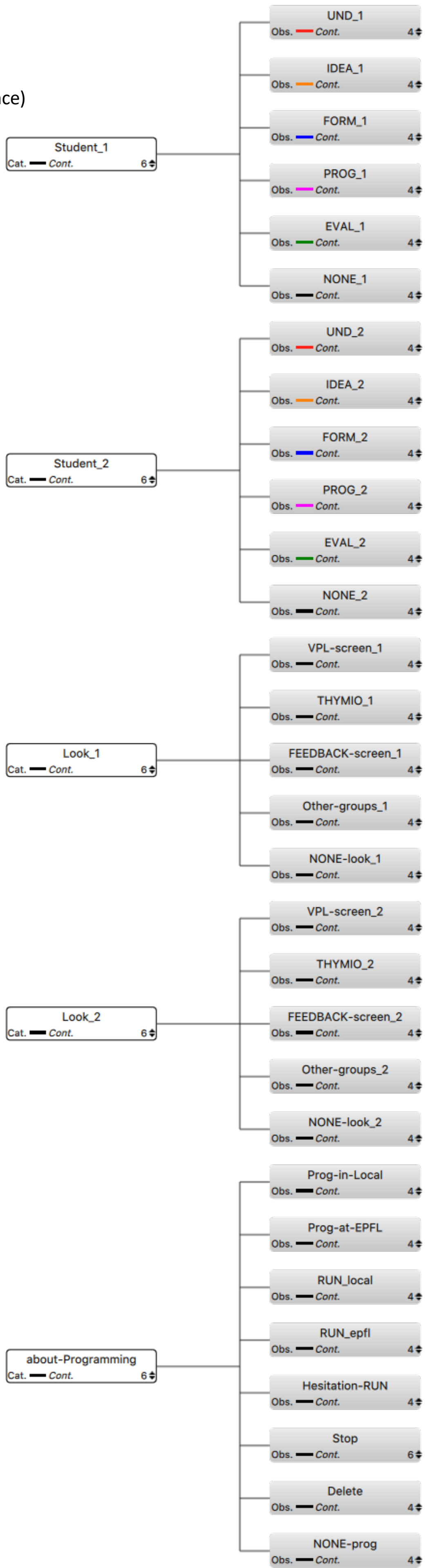
How many steps are there on this path? ....

Fill in the following table for each of the steps:

(we have started to record step 1, draw a line to separate the following steps)

Step	What should Thymio do at this step (what actions)?	How does Thymio sense its environment at this stage?	How to program it?	Test the program
1	Thymio must ...	It can pick up ... thanks to ...	If... Then...	Ok / not ok

Video Analysis Protocol
Made with Actograph
(SymAlgo Technologies, Paris, France)



Paper #4

Chevalier, M.*, El-Hamamsy, L.*, Giang, C., Bruno, B., & Mondada, F. (2021). Teachers' perspective on fostering computational thinking through educational robotics. *arXiv preprint arXiv:2105.04980*.

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Teachers' perspective on fostering computational thinking through educational robotics⋆

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[3] SUPSI-DFA, Locarno, Switzerland

⋆ This research was supported by the NCCR Robotics, Switzerland. We would like to thank the trainers and teachers who made this study possible.

⋆⋆ Morgane Chevalier and Laila El-Hamamsy contributed equally to this work

Abstract. With the introduction of educational robotics (ER) and computational thinking (CT) in classrooms, there is a rising need for operational models that help ensure that CT skills are adequately developed. One such model is the Creative Computational Problem-Solving Model (CCPS) which can be employed to improve the design of ER learning activities. Following the first validation with students, the objective of the present study is to validate the model with teachers, specifically considering how they may employ the model in their own practices. The Utility, Usability and Acceptability framework was leveraged for the evaluation through a survey analysis with 334 teachers. Teachers found the CCPS model useful to foster transversal skills but could not recognise the impact of specific intervention methods on CT-related cognitive processes. Similarly, teachers perceived the model to be usable for activity design and intervention, although felt unsure about how to use it to assess student learning and adapt their teaching accordingly. Finally, the teachers accepted the model, as shown by their intent to replicate the activity in their classrooms, but were less willing to modify it or create their own activities, suggesting that they need time to appropriate the model and underlying tenets.

Keywords: Computational Thinking · Educational Robotics · Instructional Intervention · Teacher professional development · Teacher practices

1 Introduction

Educational robotics has garnered significant interest in recent years to teach students not only the fundamentals of robotics, but also core Computer Science (CS) concepts [5] and Computational Thinking (CT) competencies [2, 3]. However, participation in an ER Learning Activity (ERLA) does not automatically ensure student learning [17], with the design of the activity playing a key role towards the learning outcomes [6]. Indeed, the lack of understanding as to how specific instructional approaches impact student learning in ER activities has been raised at multiple occasions [16]. Many researchers have even evoked the need to have an operational model to understand how to foster CT skills [10] within the context of ER activities [1, 9]. To that effect, Chevalier & Giang et al. [3] developed the Creative Computational Problem Solving (CCPS) model for CT competencies using an iterative design-oriented approach [13] through student observations. The resulting 5 phase model (Fig. 1) helped identify and understand students' cognitive processes while engaging in ER learning activities aimed to foster CT skills. By analysing the students' behaviour through the lens of the CCPS model to understand the students' thought processes, both teachers and researchers may have a means of action and intervention in the classroom to foster the full range of cognitive processes involved in creative computational problem solving. The authors concluded that a validation by teachers was essential to ensure that they could "effectively take advantage of the model for their teaching activities", not only at the design stage, but also to guide specific interventions during ER learning activities.

This article reports the findings of a study involving 334 in-service and pre-service primary school teachers, with the purpose of evaluating their perception of the model and investigating whether their own needs as users of the model are met. The Utility, Usability and Acceptability framework [18] for computer-based learning environment assessment was leveraged, as it has been previously used for the evaluation of teachers' perception of the use of educational robots in formal education [4]. More formally, we address the following questions:

RQ1: What is the perceived utility of the CCPS model?

RQ2: What is the perceived usability of the model?

RQ3: What is the acceptability of the model by teachers?

2 Methodology

To evaluate the model, the study was conducted with 232 in-service and 102 pre-service teachers participating in the mandatory training program for Digital Education underway in the Canton Vaud, Switzerland [5] between November 2019 and February 2020. The inclusion of both pre-service and in-service teachers within the context of a mandatory ER training session helps ensure the generalisability of the findings to a larger pool of teachers, and not just experienced teachers and/or pioneers who are interested in ER and/or already actively integrating ER into their practices [4]. During the ER training session, the teachers participated in an ER learning activity (see Lawnmower activity in Fig. 1 [3]) which was mediated by the CCPS model. During this activity, the teachers worked in groups of 2 or 3 to program the event-based Thymio II robot [12] to move across all of the squares in the lawn autonomously. As the robot is event-based, the participants "have to reflect on how to use the robot's sensors and actuators to generate a desired [behaviour]" [3], which requires that the participants leverage many CT-related competencies. So that teachers understand how the CCPS can be used to mediate an ER learning activity, and similarly to

Chevalier & Giang et al. (2020) [3], a temporary access blocking to the programming interface was implemented at regular time intervals.

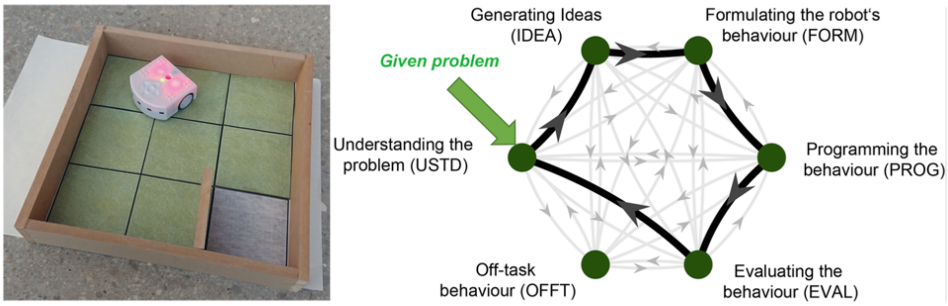

Fig. 1. The CCPS model (left) and lawnmower activity setup with Thymio (right) [3].

After the activity, the teachers participated in a debriefing session where they were asked to express what they had to do to solve the problem and the trainer grouped these comments into categories relating to CT, the CCPS model and transversal skills. The teachers were then presented the CCPS model itself and its 5 phases, together with the results of the study conducted by Chevalier & Giang et al. [3] to provide concrete testimony as to the effectiveness of the model when applied in classrooms. Finally, in an overarching conclusion about fostering CT competencies during ER activities, the trainer provided guidelines on how to design ER learning activities and intervene accordingly.

The Utility, Usability and Acceptability framework [18] then served as the basis for the teachers' evaluation of the CCPS model. As utility "measures the conformity of the purpose of the device with the users' needs" [4, 18], in the present context we consider utility with respect to student learning. Two perspectives are adopted: 1) how the use of the model helps foster transversal skills that are part of the mandatory curriculum[1] and 2) how certain intervention methods may help promote reflection in the different phases of the model. Usability on the other hand considers "the ease of use and applicability of the device" [4, 18] by the teacher, which is why the CCPS model in this case is considered in accordance with the "professional and technical actions" that teachers make use of in their daily practices[2]. Finally, acceptability "measures the possibility of accessing the device and deciding to use it, the motivation to do so, and the persistence of use despite difficulties" [4, 18]. In this case, we consider acceptability with respect to what the teachers intend to do with the model with increasing levels of appropriation. To measure the aforementioned constructs, a set of questions pertaining to each dimension was developed (see Table 1) with most responses being provided on a four-points Likert scale (1 - strongly disagree, 2 - disagree, 3 - agree, 4 - strongly agree).

[1] See transversal skills of the curriculum: plandetudes.ch/capacites-transversales

[2] See "gestes professionels": go.epfl.ch/hepvd_referentiel_competences_2015

Table 1. Utility, usability and acceptability survey [18]. Utility in terms of transversal skills considers 5 dimensions: collaboration (COL), communication (COM), learning strategies (STRAT), creative thinking (CREA) and reflexive processes (REFL)

Construct	Question
Utility of the CCPS for transversal skills (4-point Likert scale)	(COL) We exchanged our points of view / evaluated the pertinence of our actions / confronted our ways of doing things (COM) We expressed ourselves in different ways (gestural, written etc. . .) / identified links between our achievements and discoveries / answered our questions based on collected information (STRAT) We persevered and developed a taste for effort / identified success factors / chose the adequate solution from the various approaches (CREA) We expressed our ideas in different and new ways / expressed our emotions / were engaged in new ideas and exploited them (REFL) We identified facts and verified them / made place for doubt and ambiguity / compared our opinions with each other
Utility of the intervention methods (checkboxes)	What helps i) identify the problem (USTD)? ii) generate ideas (IDEA)? iii) formulate the solution (FORM)? iv) program (PROG)? v) evaluate the solution found (EVAL)? *Max 3 of 5 options : 1) manipulating the robot; 2) writing down the observations; 3) observing 3 times before reprogramming; 4) programming; 5) not being able to program*
Usability (4-point Likert scale)	The model helps i) plan an ERLA; ii) intervene during an ERLA; iii) regulate student learning during an ERLA; iv) evaluate student learning during an ERLA
Acceptability (4-point Likert scale)	I will redo the same ERLA in my classroom I will do a similar ERLA that I already know in my classroom I will do a similar ERLA that I will create in my classroom I will do a more complex ERLA in my classroom

3 Results and Discussion

3.1 RQ1 - Utility

Educational robotics learning activities are often considered to contribute to the development of a number of transversal skills (e.g., collaboration, problem solving etc...) [2]. While this perception is also shared by teachers who are pioneers in robotics [4], it is important to ensure that ER activities mediated using the CCPS model and designed to foster CT skills, are perceived by teachers at large as contributing to the development of transversal skills. The results of the survey showed that teachers found the ER learning activity with the Thymio useful to engage in transversal skills (Fig. 2), in particular collaboration, reflexive processes, learning strategies and communication, with only creative thinking being less perceived by teachers. This is coherent with the fact that the ER Lawnmower activity was conceived to promote students' use of transversal skills to help the emergence of related CT competencies and suggests that the use of the CCPS model in designing ER learning activities helps teachers see and strengthen the link between ER, transversal skills and CT, confirming the results of [4] with teachers who were novices. Although in the mandatory curriculum teachers are taught to evaluate transversal skills, little indication is provided as to how to foster them. The use of ER learning activities informed and mediated by the CCPS model can provide a concrete way to foster skills already present in the curriculum and ensure that students acquire the desired competencies.

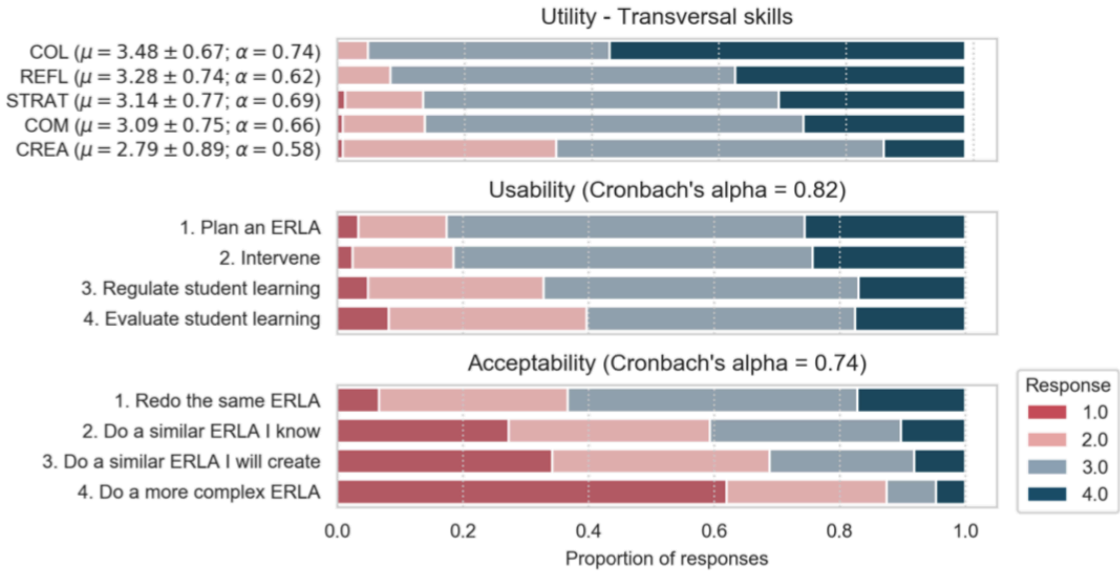

Fig. 2. Teachers' perceived utility (with respect to fostering transversal skills), usability and acceptability of the CCPS model. For each transversal skill we report the mean and standard deviation μ±std, and Cronbach's α measure of internal consistency.

To clarify the link between the CCPS model and the employed intervention methods, the teachers were asked to select a maximum of three intervention methods that they believed were useful to engage in each of the phases of the CCPS model (see Fig. 3). The element which emerges as the most relevant for all the phases of the model is the possibility of manipulating the robot, thereby reinforcing the role of physical agents in fostering CT skills [8]. This however is dependent on the fact that the Thymio robot provides immediate visual feedback through the LEDs in relation to each sensor's level of activation. This highlights once more the importance of constructive alignment in ER learning activity design [7] which stipulates the importance of the robot selection in relation to the desired learning outcomes. The second most popular choice was to write down the observations, likely because this constitutes a means of specifying what happens with the robot in the environment. The written observations then become a "thinking tool" that supports modelling and investigation [15]. Surprisingly, and although the teachers were introduced to the fact that unregulated access to the programming interface tends to lead to trial and error behaviour [3], programming was often selected as being useful to foster the different CT phases, whilst not being able to program was one of the least selected. Only in the case of idea generation did both programming and not programming receive an equal number of votes. We believe that the frequent selection of programming is due to the fact that the question was based on their experience as the participants, and therefore the need for a high sense of controllability [14], in the ER learning activity and not on their experience as a teacher leading the activity in the classroom.

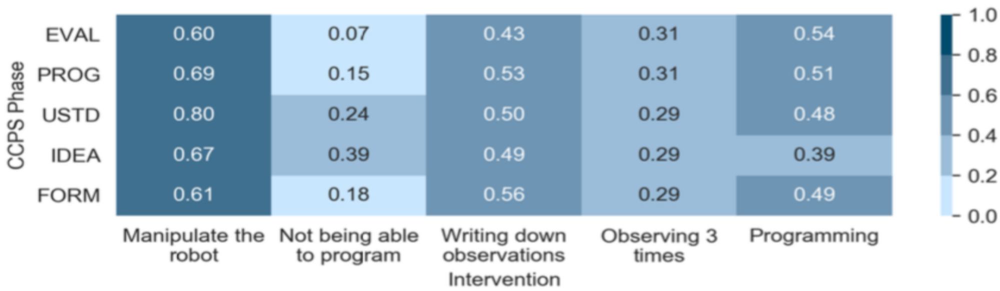

Fig. 3. Teachers' perception of the link between intervention methods and the different phases of the CCPS model. For each phase of the model and intervention method, the proportion of teachers having selected the approach as relevant is shown.

To summarise, on the one hand, teachers perceive the usefulness of promoting transversal skills that they are familiar with, as they are already part of the curriculum. On the other hand, they do not perceive what research has shown to be useful to promote CT competencies, likely because it was not part of the curriculum until now. Therefore, experimentation in their classrooms is necessary, as well as further training to help them acquire a more critical view of ER learning activities and to understand the impact of specific intervention methods on the development of students' skills.

3.2 RQ2 - Usability

With respect to the usability of the CCPS model in the teaching profession, responses were globally positive (see Fig. 2, $\mu = 2.89$, std= 0.78, Cronbach's $\alpha = 0.82$). Teachers believed that the CCPS model could be used to plan and intervene during an ER learning activity (over 80% of positive responses), likely due to the guidelines provided during the theoretical presentation. However, the link between the CCPS model and student learning was less evident for teachers: 66% believed it could be used to regulate student learning and 60% that it could be used to evaluate student learning. Both constructs are related by the need to assess students and understand where they stand in terms of the overall learning objectives. Although this shows that teachers need to be taught how to identify the phases in which the students are to be able to use the CCPS model to its full extent, this is also highly linked to the difficulty found in both the ER and CT literature in terms of assessment of learning and/or transversal skills [8, 9].

3.3 RQ3 - Acceptability

The question of acceptability here targets teachers' intent to use the CCPS model in their practices. Intent to use is considered at progressive levels of appropriation (see Fig. 2), which is why it is not surprising to find that while teachers might be willing to conduct the same ER learning activity in their classrooms (64%), less are willing to adapt the activity (40%), create their own custom one (32%), and conduct a more complex one (20%). One can put this in relation with the Use-Modify-Create (UMC) progression [11] which was developed to scaffold student learning in CT contexts. Teachers need to start by using the model in a given ER learning activity to gain in self-efficacy. Only then will they be able to progress to the next stage where they feel comfortable adapting the use of the model to their teaching style and to the individual students. Finally, teachers will reach a level where they create their own ER pedagogical interventions to foster CT competencies. One must however note that intent is likely influenced by external factors (e.g. time or access to the robots, frequent barriers to the introduction of ER in formal education [4,5]).

4 Conclusion

Provided the prominent role that teachers play in the integration of ER and CT in formal education, this study investigated teachers' perception of an operational model to foster Computational Thinking (CT) competencies through ER activities: the Creative Computational Problem Solving (CCPS) model [3]. Three research questions were considered in a study with 334 pre-service and in-service primary school teachers: What is the perceived utility (RQ1), usability (RQ2) and acceptability (RQ3) of the CCPS model? While teachers found that the activity design and intervention methods employed were useful to foster transversal skills (RQ1), their perception of the utility of the intervention methods on the different cognitive processes defined by the CCPS model (RQ1) was somewhat unexpected. In terms of the usability (RQ2), teachers perceived how they could design an activity and intervene using the model, but were less able to perceive how the model could be used to assess where the students were in terms of learning and regulate the activity to mediate their learning. The findings of RQ1 and RQ2 support the importance of training teachers to recognise and understand the different cognitive processes to intervene adequately and be able to differentiate their teaching per student, rather than adopting a unique strategy for an entire class.

To help teachers implement ER learning activities in the classroom and gain in autonomy to create their own activities that foster CT skills (RQ3), it seems relevant to alternate between experimentation in classrooms and debriefing during teacher training and go beyond providing pedagogical resources. To conclude, the operationalisation of ER to foster CT skills must also consider the key role that teachers have to play in the introduction of any such model and its application in formal education.

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