Thèse n° 9835

Supporting Teachers’ Orchestration in Robot-mediated Classrooms

Présentée le 10 mai 2023

Faculté informatique et communications
Laboratoire d’ergonomie éducative
Programme doctoral en robotique, contrôle et systèmes intelligents

pour l’obtention du grade de Docteur ès Sciences

par

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École
polytechnique
fédérale
de Lausanne

2023

Challenge ACCEPTED!

Acknowledgements

Firstly, and most importantly, I would like to thank my thesis director, Professor Pierre Dillenbourg, who gave me the opportunity to conduct research in the field of educational technology. Without his guidance, finishing this thesis for me alone would have been impossible. He taught me that a valuable research is the one that truly impacts teachers and students' life in classrooms. I hope I will continue sharing great moments with him, whether it is in the CHILI lab or on a ski lift!

I would also like to thank my Jury members: Profs. Denis Gillet, Dimitris Alimisis, Luis P. Prieto and Francesco Mondada for their availability, taking the time to evaluate my work and their comments that helped the quality of the thesis.

I would like to thank my co-supervisor, Dr. Barbara Bruno, who is the most accurate researcher I truly appreciate her detailed and thoughtful feedback on my writing, always saying *"Sina, be consistent in what you mean"*. She has been my support in the highest and lowest part of my PhD path. I have no doubt she will be an amazing professor. I will miss our chit-chats over coffees on Iran and Europe's history.

I also should thank the postdocs I have worked with during the four years of my PhD; starting with Dr. Wafa Johal with whom I had my first interview for this position. I would like to thank her for her trust in me and her inputs during the first year of my PhD. Working with Jennifer Olsen has taught me the principles of research in human-computer-interaction and working with Stian Haklev has taught me the first steps in software engineering. Especially, I would like to thank Prof. Aditi Kothiyal for her thoughtful and inspiring comments to make my thesis a valuable contribution in the education field. She has been always available to listen to my problems, help me coming with solutions and supporting me in all steps of research from experiment planning to data collection, analysis and writing the thesis.

This thesis is part of ANIMATAS project: my thanks to Prof. Mohamed Chetouani to manage the project. Indeed, being in this project was an amazing opportunity for me to expand my professional network and discover Europe.

I would like to thank all the teachers and students who participated in my studies; most of these studies have been performed in Swiss private and public schools. I am very thankful for their time and the their support. I would like to especially thank Melissa Skweres and Sophia Reyes Mury for their great support in making connection with schools.

The CHILI team has one of the best atmosphere a PhD student can wish for; a humanoid, friendly environment allowing me to focus on my research but also have a feeling to be part of a big family. I start my thanks with the true boss of the lab, Florence Colomb; she has supported me from the first day of being accepted in the lab with all the travel tickets, invoices and basically every question I ever had about EPFL and Switzerland. I hope one day EPFL and SBB websites listen to her to make a more user-friendly interfaces! Hala Khodr, my Chilian sister who has helped me with any questions with/from/of Cellulo robots. Utku, the nicest person on earth, with whom, I have shared lots of great moments in the lab. My thanks to all other Chilians that I've met in these four years: Arzu, Ayberk, Kevin, Lucas, Richard, Jade, Laila, Jauwairia, Zhenyu and all others that I might have forgotten to mention here.

I would like to thank the bachelor and master students at EPFL whom I worked with, including Léo Hauser, Guillaume Follonier, Lorenzo Rovati, Juliette Challot. I hope I have been a good supervisor for them.

Throughout the years of PhD, I have been accompanied by amazing friends. I start with my dear Iranian friends; Milad Ejtehadi, the most honest and caring person I know which supported me though one of my most difficult moments in my life before starting this PhD. I have always enjoyed talking with Amirali Abazari and Ehsan Azad about life and I wish I could see them in person. Soheil Kianzad has been a great mentor for me in my career path. Ashkan gave me the inspiration to become more green in life. Being in Switzerland has given me the opportunity to find friends that I am grateful for; Dr. Louis Faucon,my companion in chess (which I hope one day I can win him) and my great mentor in software engineering. My dear friend, Dr. Thibault Asselborn who has been there for me during the most difficult moments of my PhD. My only wish for him is to practice more to be as good as me in Ski! My most handsome friend, Dr. Daniel Tozadore, which sharing beers with him has helped me to survive the PhD life. I hope one day I will discover his beautiful country and teach his son/daughter how to live. My dearest thanks to Natalie Kummer, who has always supported me with the best gifts of Switzerland, Ski, chocolate and fondue, whenever I was sad with PhD life or fallen on ski slopes! I have shared the best moments during the years of my PhD with her.

Last and most importantly, my family has been a true support for me; I would like to thank Borzu Shahmoradi, my uncle who gave me the precious gift of loving mountains and the spirit of being a strong man in life. My greatest thanks to my mom, she was the one who motivated me to start this thesis, when I was lost in the path of my career. My thanks would not be enough to my father, who has devoted his life to education and has been an inspiration for me. I remember the day he told me that this position will be my best choice and he was indeed right! I wish the best for my sister, Sara, in the beautiful journey she started recently as entering university.

Lausanne, 08 January 2023 S. SH.

Abstract

To bring educational robots to classrooms, we need to consider teachers' self-efficacy and challenges in managing a robot-mediated classroom, and how to support them in overcoming these challenges. Orchestration tools are designed to support teachers by providing real-time information on the students' actions and progress within the activity, at various levels of detail and scope, as well as levers to control the flow of the activity. In order for orchestration tools to be effective and useful, their features should be designed according to the needs of the teachers in each specific classroom context.

This thesis starts by investigating the orchestration practices enacted by teachers in authentic robot-mediated classrooms, i.e. during classroom activities in which students, individually or in groups, are envisioned to interact with educational robots, and find the teachers' needs that can be supported by orchestration technologies. Building on the results of such classroom observations, the thesis then discusses the design and classroom evaluation of orchestration tools for robot-mediated classrooms. Concretely, this thesis makes three contributions.

- It provides an overview of the challenges that teachers face in their practice, when orchestrating robot-mediated math activities and specifically to the purpose of orchestrating math class discussion to be productive. The results are based on more than twenty hours of in-session analysis of teachers' behaviour and class discourse in eight math sessions.
- It analyses the results of how teachers orchestrate robot-mediated math activities and evaluate whether orchestration tools can improve their orchestration practices. I design, develop and study the usage, usability and usefulness of a novel orchestration tool, called CelloRoom, in the context of a series of robot-mediated activities aiming to teach the mathematics concepts of coordinate system and line slope in in-person classrooms to children aged 7-14 years old. Across two design iterations, eleven teachers in different primary/secondary schools across Switzerland adopted the mathematical robot-mediated activities in their classrooms, using two versions of CelloRoom for a total of 14 sessions and more than 200 students. The findings emphasize the importance of investigating teachers' orchestration practices by analysing class audio/video recording, to evaluate the usefulness of orchestration tools in class time.
- It proposes a set of novel quantitative measures to describe and assess how teachers

perform the practices of orchestrating productive math discussions, defined by Stein et al., 2008, namely monitoring students' mathematical thinking, selecting and sequencing students' solutions in class to emerge mathematical ideas and connecting these ideas to the underlying learning goal of the activity. These measures were used the evaluate the usefulness of CelloRoom 2.0 in supporting teachers' orchestration of productive math discussions.

Our findings highlight the benefits that orchestration tools can bring for the orchestration of robot-mediated classroom activities by teachers: the teachers involved in our studies could get aware of robot failures in the class quickly and reliably, could adapt the activity sequence on the fly and found students' data visualization helpful to create discussion in the classroom, especially for selecting and sequencing students' solutions. Building on these findings, the thesis finally provides guidelines for the design of orchestration tools in the specific context of robot-mediated math activities.
Keywords: Educational Robotics, Orchestration Tools, Classroom Orchestration, Human-Computer-Interaction, Orchestrating Productive Math Discussion, Classroom Observation.

Résumé

Pour introduire les robots éducatifs dans les classes, nous devons prendre en compte l'auto-efficacité des enseignant-e-s et les défis de gestion d'une classe médiatisée par des robots, ainsi que la manière de les aider à surmonter ces défis. Les outils d'orchestration sont conçus pour aider les enseignant-e-s en leur fournissant des informations en temps réel sur les actions et le progrès des élèves au sein de l'activité, à différents niveaux de détail et de portée, ainsi que des leviers pour contrôler le déroulement de l'activité. Pour que les outils d'orchestration soient efficaces et utiles, leurs fonctionnalités doivent être conçues en fonction des besoins des enseignant-e-s pour chaque contexte spécifique de classe.

Cette thèse commence par étudier les pratiques d'orchestration mises en œuvre par les enseignant-e-s dans des classes authentiques médiées par des robots. Ceci implique donc l'étude des activités de classe dans lesquelles les élèves, individuellement ou en groupe, sont censés interagir avec des robots éducatifs, afin d'identifier les besoins des enseignant-e-s qui peuvent être pris en charge par les technologies d'orchestration. En s'appuyant sur les résultats de ces observations en classe, la thèse aborde ensuite la conception et l'évaluation d'outils d'orchestration employés dans des classes médiatisées par des robots. Concrètement, cette thèse apporte trois contributions.

- Elle fournit une vue d'ensemble des défis auxquels les enseignant-e-s sont confronté-e-s dans leur pratique, lors de l'orchestration d'activités de mathématiques médiatisées par des robots, et plus spécifiquement dans l'objectif d'orchestrer la discussion en cours de mathématiques pour augmenter sa productivité. Les résultats sont basés sur plus de vingt heures d'analyse du comportement et discours des enseignant-e-s en classe dans huit sessions de mathématiques.

- Elle analyse comment les enseignant-e-s orchestrent les activités de mathématiques médiatisées par des robots et évalue si les outils d'orchestration peuvent améliorer leurs pratiques d'orchestration. Je conçois, développe et étudie l'utilisation, la utilisabilité et l'utilité d'un nouvel outil d'orchestration, appelé CelloRoom, dans le contexte d'une série d'activités médiées par des robots. Cette activité vise à enseigner les concepts mathématiques en lien avec des systèmes de coordonnées et des équations de pente dans des classes en présentiel à des enfants âgés de 7 à 14 ans. Au cours de deux itérations de conception, onze enseignant-e-s de différentes écoles primaires et secondaires de Suisse ont adopté les activités mathématiques médiatisées par des robots dans leurs classes, en utilisant deux versions de CelloRoom pour un total de 14 sessions et plus de 200 élèves. Les résultats soulignent l'importance d'étudier les pratiques d'orchestration des enseignant-e-s en analysant l'enregistrement audio/vidéo de la classe, afin d'évaluer l'utilité des outils d'orchestration en classe.

- L'étude propose un ensemble de nouvelles mesures quantitatives pour décrire et évaluer la façon dont les enseignant-e-s mettent en œuvre les pratiques d'orchestration de discussions mathématiques productives telles que définies par Stein et al. 2008. Ceci concerne le suivi de la pensée mathématique des élèves, la sélection et la mise en séquence des solutions des élèves en classe pour faire émerger des idées mathématiques et la connexion de ces idées aux objectifs d'apprentissage sous-jacents de l'activité. Ces mesures ont été utilisées pour évaluer l'utilité de CelloRoom 2.0 pour aider les enseignant-e-s à orchestrer des discussions mathématiques productives.

Nos résultats mettent en évidence les avantages que les outils d'orchestration peuvent apporter aux enseignant-e-s pour l'orchestration d'activités de classe médiées par des robots. En effet, les enseignant-e-s impliqués dans nos études ont pu être informés des défaillances du robot dans la classe de manière rapide et fiable, ont pu adapter la séquence d'activité à la volée, et ont trouvé la visualisation des données des élèves utile pour créer une discussion en classe, en particulier pour sélectionner et séquencer les solutions des élèves. Enfin, sur la base de ces résultats, la thèse fournit des lignes directrices pour la conception d'outils d'orchestration dans le contexte spécifique des activités mathématiques médiées par des robots.
Mots-clés : Robotique éducative, outils d'orchestration, orchestration en classe, interaction homme-ordinateur, orchestration de discussions mathématiques productives, observation en classe.

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1 Introduction

1.1 Context

Educational Robotics (ER) is a field of study that aims to improve the learning experience of people through the creation, implementation, improvement, and validation of pedagogical activities and tools in which robots play an active role (Scaradozzi et al., 2019). There are multiple different types to categorize robots (e.g. size, being mobile/static, type of interaction, etc). Here, I choose the following two types of categorization, according to Belpaeme et al.'s review on the robots used in education (Belpaeme et al., 2018), which is illustrated in Figure. 1.1:

- Table-top robots (small size, mobile, without social interaction with the user), utilized in two ways: a) as robot-mediated platforms with screen-based or tangible interfaces suitable for practicing programming (as shown in Fig. 1.1) in the context of open-ended, project-based activities (Eguchi, 2014); b) as hand-held tools for learning activities that are shaped based on physical learner-robot-interaction (Mubin et al., 2013), e.g. to teach handwriting (Asselborn et al., 2018) and mathematics (Özgür, Johal, et al., 2017). These robots have reached a maturity level that made it possible to integrate them into real classroom conditions Chevalier et al., 2016b
- Social robots, for example used to teach foreign languages to children (Chang et al., 2010) or storytelling tasks (Mutlu et al., 2006) which rely on social (e.g. verbal or gestural learner-robot-interaction). *Social robots are not studied in this work*, because of these two reasons: firstly, most social robots are used in one to one interactions between the robot and the child while studies on classroom orchestration happen in a scenario including multiple students and a teacher. Secondly, most social robots are used as tutors in the learning activities, rather than as a tool that students interact with it, hence the orchestration mechanism would be incorporated inside the robots software itself.

Research on ER has shown that teachers are motivated by a variety of reasons to use robots in

Figure 1.1: Different categories of robots used for education. From left to right: NAO (Le Denmat et al., 2018), Thymio (Chevalier et al., 2016b) and Cellulo (Özgür, Lemaignan, et al., 2017). Thymio and Cellulo are both educational robots, with Thymio being a table-top platform for CS and CT skills acquisition, while Cellulo is a robot aiming to enhance and mediate the acquisition of disciplinary content via the students' interaction with it. NAO belongs to the category of social robots, more expensive and less used in classroom settings.

their teaching, including:

- Teachers feel that by using robots in their teaching they learn something new or they can be professionally more efficient (Karim et al., 2015). Based on a research done in 2016 among more than 200 teachers in Switzerland, teachers who could adopt robots in their classrooms had strong intrinsic motivations to be a competent teacher. For other teachers, even though extrinsic motivations motivated them to use the robots for some time, they gave up because of barriers in classroom adoptions of robots, like their lack of technical knowledge about robots (Chevalier et al., 2016b).
- Robots helps learners experience hands-on learning activities (Mataric et al., 2007) which translate the abstractness of lessons in mathematics to real-world problem-solving activities (Nugent et al., 2010).
- Robots are engaging and attract the attention of students with different ages (Riedo et al., 2012). They have been successful in increasing students' participation and as a result could be used to support learning of some specific skills such as sequencing skills (Evripidou et al., 2021).
- Robots create a physical workspace for collaboration among students (in contrast to screen-based activities). In several studies, robots have facilitated running collaboration scripts in classrooms (Atmatzidou and Demetriadis, 2012; Kagan, 1989) which led to an increase in the students' interest and their active participation.
- Robots facilitate applying certain learning theories in classrooms, like constructivism (Fosnot, 2013) and constructionism (Harel and Papert, 1991). Students can *construct*

their knowledge to program the robot or solve the underlying problem (Alimisis, 2013). More importantly, robots were an inspiration for developing constructionism, a learning theory, based on constructivism that emphasizes hands-on learning and stresses the importance of tangible outputs for learners(Alimisis and Kynigos, 2009).

Apart from the above-mentioned benefits that robots can bring for learning, they could create some challenges for teachers when using them during classroom teaching. In below, I mention the three most important ones:

- Robots are complex technologies for teachers compared to other technologies in classrooms. Teachers have to prepare the robots before the class, for example by making sure they are charged enough. Technical failures are unpredictable events that could happen during learning activities because of robot design problems or inappropriate usage by students, especially children. In ER classrooms, the added complexity of robots increases the possibility of technical failures compared to other Technology-Enhanced Learning (TEL) classrooms.

- robot-mediated activities include a considerable part of problem-solving tasks (Mubin et al., 2013), therefore students may use a variety of learning strategies, creating an unpredictable learning environment (Jormanainen, 2013), which makes it hard for teachers to follow students' works.

- As mentioned earlier in this section, robot-mediated activities are often constructivist activities. Therefore, according to teachers' roles in constructivist classrooms, they should actively facilitate the connections between students' activity and the underlying conceptual knowledge by creating discussion in the classroom as debriefing lectures. Such lectures require teachers to orchestrate a feedback and discussion session to aggregate the students' reflections on their activity, to identify new ideas from the students' work and build on it in their instruction (Hand et al., 1997; Kriz, 2010). Here, the teachers' challenges are firstly to debrief the lesson at the right moment (Schwartz and Bransford, 1998); so teachers need to have control over the sequence of the activities and be able to pause/resume students' activities easily. Secondly, teachers need to prepare the discussion based on the students' contributions which requires real-time data (from the students' interactions with the robot-mediated activity) (Do-Lenh et al., 2012).

When adding a learning technology to the class environment, one of the most important criteria for teachers is the quality of classroom management (Do, 2012). They value a technology that makes them feel *"this works well in my class"* (Dillenbourg et al., 2011). Research on classroom orchestration and particularly orchestrating Technology-Enhanced-Learning (TEL) classrooms has tried to identify what makes teacher feel that this technology works well in classrooms by considering the usability of a technology at class level rather than individual or group level (Dillenbourg et al., 2011). According to this perspective, in addition to designing a technology for learning, researchers should also design the technology for teaching and consider the role of teachers in such a scenario.

Robots are not the first technology that come to classrooms. Researchers have explored the usage of many other technologies in schools, like tablets (P. Wang et al., 2017) and table-top learning technologies (Do, 2012). Similar to robots, these technologies also have created challenges for teachers by changing the orchestration process in the classroom. For instance in AI-enhanced classrooms that students use intelligent tutoring systems teachers have felt "out of the loop" while there are certain situations in which students need teachers' support. Another challenge when bringing screen-based learning technologies to classrooms, is that as a result teachers find it difficult to monitor students' activities, because the screen acts as a barrier between teacher and student and makes teacher-student-communication more difficult. One of the proposed solutions to such problems is to use classroom orchestration technologies (or simply orchestration tools) to assist teachers in one or more aspects of their teaching and classroom management (Amarasinghe et al., 2020) or learning dashboards (Martinez Maldonado, Kay, et al., 2012). Each tool provides several orchestration functionalities that, depending on the context, are designed to assist teachers in one or several aspects of classroom orchestration, for example by providing students' traces of learning activity (Verbert et al., 2013) or making teachers able to control the activity flow (Amarasinghe et al., 2020). The challenge of designing orchestration tools remains that orchestration features should be designed according to the context and an orchestration functionality that works in a context might be not useful in another one.

In the increasing trend of bringing robots to classrooms as learning technologies, there is a mutual need between research on ER and TEL classroom orchestration. ER researchers are trying to bring the benefits of robotics to create new learning activities but they need classroom orchestration methods to support teachers in adapting the proposed activities. At the same time, researchers on TEL classroom orchestration are interested in evaluating the usability of ER in classrooms and focus on teachers' satisfaction with providing orchestration tools before developing any further application of the technology.

In order to successfully open the doors of classrooms to ER, teachers' challenges with managing such classrooms need to be understood. Therefore, the heart of this PhD will be devoted to this matter and later understand how the orchestration tools affect the teachers' behaviours in robot-mediated classrooms. This thesis will contribute to realistically scale-up the use of ER in classrooms and apply the classroom orchestration principles to a new and challenging context.

1.2 Classroom Orchestration, Orchestrating Productive Math Discussions and Orchestration Technologies

Research in learning sciences has evolved from testing learning theories in individual/group condition at laboratory settings to more complex scenarios in the real contexts, including classrooms. Classroom is a socially-complex environment with different layers of activities (individual, group or class) and unpredictable events (Jormanainen, 2013). Classroom orchestration research came as a way to support the transition from lab studies to authentic classroom ones. Classroom orchestration models started to receive attention from the learning community in the late 2000s (Dillenbourg et al., 2011), mostly by researchers in Computer-Supported-Collaborative-Learning (CSCL). In its classical definition, orchestration refers to *how the teacher manages in real-time the multiple learning processes occurring in the classroom at multiple social levels.* In contrast to personalized learning, it emphasizes the role of the teacher in managing real-time class events, including collaborative and class-level activities (Martinez-Maldonado et al., 2013).

In recent years, this topic has also been under attention in the concept of orchestrating TEL classrooms. In this research field, orchestration is re-defined as *how to address the challenges of coordinating the complexity of conducting learning activities with new technologies* (Prieto et al., 2011). Orchestration starts even before the learning activity is conducted in classroom by planning the activities in several social layers and over time, but it mainly deals with coordinating real-time classroom events and interventions in response to what is happening in the classroom. In other words, orchestration is the process of monitoring students' learning activity and define consequent on-the-fly adaptations of the classroom workflow (Dillenbourg et al., 2011).

Class discussions are an integral part of effective teachers' practices in constructivist and consequently ER classrooms (McCormick and Donato, 2000), as there is strong relation between these two (Alimisis et al., 2019). Particularly, research has been focused on improving orchestration of classroom discussion to be *productive* (Stein et al., 2008). Students' participation is a very important indicator of a productive discussion, which implies that students should take ownership of the conversations in the discussion (Abdullah et al., 2012). To make orchestrating whole-class discussion *productive*, teachers must find ways to converge a wide range of students' responses to make the connection between the learning activities and their learning goal *without direct telling* (Lobato et al., 2005; Stein et al., 2008). To do this, students' responses should be developed and then build on each other collectively (Fennema et al., 1996; Stein et al., 2008). If class discussions are orchestrated productively, empirical studies suggest they can develop meta-cognitive behaviors in students and help them become expert problem solvers (Evans and Dawson, 2017), and finally have a positive impact on their learning (Stein et al., 2008).

A number of orchestration tools have been successful in supporting teachers in dealing with new technologies in their classrooms (Holstein et al., 2019).*Chao* for activities with tablets (P. Wang et al., 2017), *Class-on* for laboratory sessions (I. G. Rojas et al., 2011), *Lantern* for recitation activities (ALAvI, 2011), *FROG* for collaborative activities (Haklev et al., 2017), etc. These tools provide various information including help-seeking behaviour (who needs intervention?), time-progress of whole class for activities like quiz, frequent students' mistakes, students' exercise status, collaboration patterns, etc (Martinez-Maldonado et al., 2014b). These tools, which I review more in details in the next chapter, constitute the foundation I start from for the design of an orchestration tool for ER classrooms that can be used to orchestrate productive discussions.

1.3 Research Objectives

1.3.1 Project Overview

This research is part of *ANIMATAS*[I], a MSCA – Marie Skłodowska-Curie Actions project with the goal of bringing robots to classrooms. My research objective is to **Studying the orchestration of robot-mediated classrooms**. In this way, I have two sub-objectives:

- Understanding teachers' needs and practices in robot-mediated classrooms that can be supported by orchestration tools.

- Designing an orchestration tool for robot-mediated classrooms and study its usage, usability and usefulness to support teachers in facing their needs and improve their orchestration routine.

To design the orchestration tool, called CelloRoom, I follow design-based research methodology (F. Wang and Hannafin, 2005) which accordingly, users should be involved in all the steps from design to in-the field study through iterative cycles. Figure. 1.2 shows the cycle followed in the design-based research of my thesis. The focus of this research is on in-the-field evaluation, collaboration between users and researchers and connecting the outcomes of each iteration phase with the development process, i.e., refining CelloRoom through different phases of design sequentially. The final goal is to provide design guidelines and principles that can be informative for practitioners and designers of orchestration tools in the context of robot-mediated classrooms.

[I] website: www.animatas.eu

1.3.2 Research Questions & Methodology

RQ1: What are the teachers' needs, that can be supported by orchestration tools in: 1) orchestrating ER classrooms based on Prieto et al.'s framework (Prieto et al., 2011) and 2) orchestrating productive math discussion based on Stein et al's framework (Stein et al., 2008)?

The first step in our research, described in the third Chapter, is to study an ER classroom from a general orchestration perspective and identify teachers' needs (also called a need-finding study in the literature (Lawrence et al., 2021)). I look at teachers' actions in the classroom under the lens of the well-known TEL classroom orchestration model (Prieto et al., 2011) which identifies five most important aspects for characterising a TEL classroom, namely design/planing, management, adaptation, awareness and role of the other actors. After identifying the context, I hypothesized that there could more context- specific needs, which requires a second round of need-finding study. Therefore, in the sixth chapter, I look at how teachers orchestrate productive math discussions in the context of a robot-mediated classrooms, based on the Stein et al.'s framework (Stein et al., 2008) to find their needs in this regard.

Answering this question helps to understand: 1) which orchestration aspects are more critical for ER classrooms and 2) what are the pitfalls of orchestrating productive math discussions and how they should be taken into account while designing orchestration tools. Our methodology will be based on interviews with teachers and direct observations of their class sessions with taking note (in Chapter 3) and class recordings (in Chapter 6), following the rationale that design of technologies for teachers in classrooms should put classroom observations at the heart of the design process (Peddycord-Liu et al., 2019).

RQ2: How should orchestration tools be designed for robot-mediated classrooms to address the teachers' needs found in RQ1?

Answering this question would result in designing an orchestration tool, on the basis of direct classroom observation and teachers' feedback. I firstly review the functionalities provided by successful orchestration tools in the literature and look for the ones that could potentially address the specific teachers' needs arising in robot-mediated classrooms, identified in RQ1. As shown in Figure. 1.1, I iteratively improve the design of the orchestration tool through two iteration phases which focus on classroom studies. It is important to also include teachers' feedback as part of the iterative design cycle by groups studies with teachers.

RQ3:How do teachers use the orchestration tool, designed in RQ2, to orchestrate robot-mediated classrooms?

The third research question (Figure. 1.2) studies the usage of the orchestration tool prototype on teachers' orchestration patterns in classroom. After designing the orchestration technology,

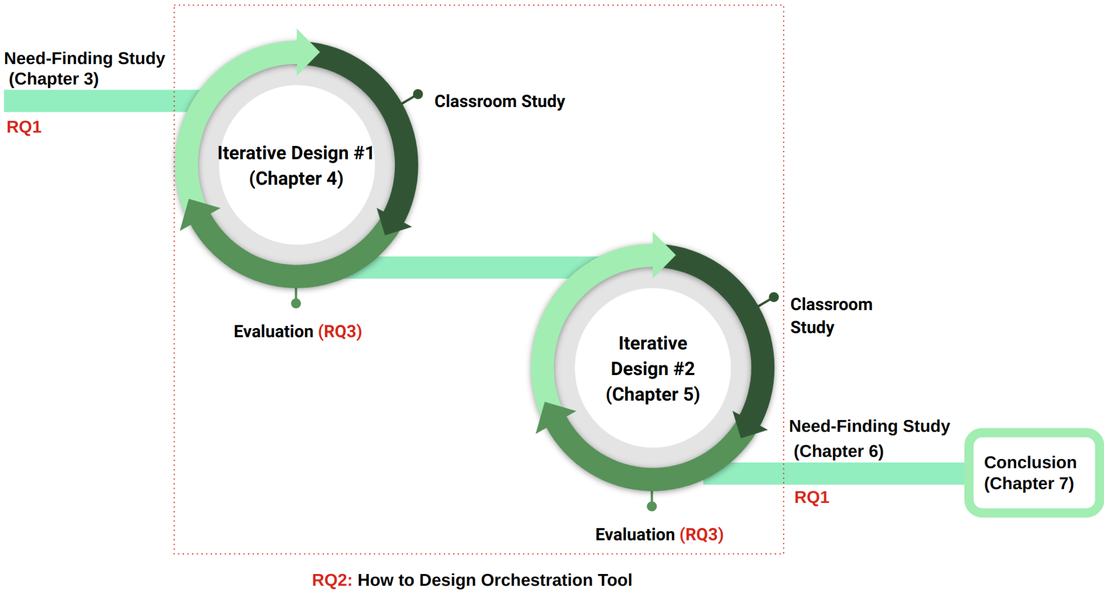


Figure 1.2: The thesis overview: as a first study in Chapter 3, I explore the orchestration process in robot-mediated classrooms to find teachers' needs (answer to RQ1). The orchestration tool (called CelloRoom) is built through two iterations incrementally, according to the methodology outlined for RQ2. Each iteration is itself a design cycle. Throughout the fist iteration, I explain the first iteration cycle and evaluate its usage in classrooms in Chapter 4 (based on the methodology identified to address RQ3). Based on the results of the first iteration, designing the prototype in the second iteration continue in Chapter 5. As a continuation to the design process, in Chapter 6 I explore how teachers perform the practices of orchestrating productive math discussions in robot-mediated classroom to find their needs. Finally, the results and contributions are summarized in Chapter 7 as thesis conclusion.

having it field-tested and evaluated by teachers and incorporating their feedback in the design process is crucial to ensure that the proposed solution effectively addresses new and existing orchestration challenges and teachers' needs (Lawrence et al., 2021).

My analysis is mainly descriptive, with some further inferences about the *usage* (how much the tool has been used by stakeholders), *usability* (how easy is it to use) and *usefulness* based on the theoretical frameworks of reference in literature; in Chapter 4, I use the three of five characterizing orchestration aspects of Prieto's orchestration framework that directly relate to real-time teachers' behaviours in class time (namely, awareness, adaptation and management) as a basis to evaluate teachers' usage. In Chapter 5, more precisely, I focus on evaluating the usefulness of the orchestration tool in supporting teachers in performing practices of orchestration of productive math discussions (Stein et al., 2008).

Most studies use self-reported data as the main data source for evaluation, in the forms of interviews (Ruiz et al., 2016) or feedback surveys (Kim et al., 2016). To complement such subjective information, recent studies have also used tracked data during class time. Logging teacher's interactions with the orchestration tool has been the most used among such data sources (Schwendimann et al., 2016), but researchers have also considered more rich data sources like teachers' audio/video recording (Amarasinghe et al., 2020) or students' learning gain (Kim et al., 2016). As our methodology, I complement the interaction logs of the orchestration tool and teachers' interviews with richer data sources like audio/video classroom recordings to have a more precise and rich analysis of teachers' orchestration behaviour.

1.4 Thesis Contributions

The thesis argues that to the purpose of improving the orchestration of robot-mediated classrooms, I should carefully consider the role of teachers and support them by providing adequate orchestration tools. In this regard, this thesis:

- Related to the RQ1, it explores teachers' orchestration behaviour in robot-mediated classroom by observing robot-mediated classrooms and finds their needs that can be supported via orchestration tools by:
  - Observing teachers' behaviours in robot-mediated classrooms, characterising their orchestration based on Prieto's framework Prieto et al., 2011 and indicating the challenges and potential benefits of orchestrating robot-mediated classrooms.
  - Exploring teachers' performance in practices of orchestrating productive math discussion in robot-mediated classrooms by analysing teachers' voices and evaluating their behaviours thanks to the proposed quantitative metrics, based on Stein et al' framework (Stein et al., 2008).
- Related to RQ2, it presents the architecture of CelloRoom (which includes a set of orchestrated robot-mediated activities to teach basic concepts of mathematics together with an orchestration tool), and refines it according to the principles of design-based research.
- Related to RQ3, it evaluates the classroom usage of CelloRoom in two stages to determine its effects and finally proposes a set of guidelines for designing orchestration tools for robot-mediated classrooms.

The thesis provides three specific elements that differentiate it from related works in classroom orchestration tools and ER :

- The studies specially focus on classroom settings with realistic learning scenarios which is novel especially in the field of ER and makes the results more valuable.
- With CelloRoom, the thesis validates a set of learning activities for primary and secondary education and empowered 11 teachers to autonomously conduct them in their classrooms.

- According to the studies in classroom orchestration tools, the thesis focuses on the less-touched learning context of primary and secondary education, which is of high value since it testifies their usage in a new context.

1.5 Thesis Road-map

Chapter 2 presents the relevant models and background from literature together with an overview of the related work in the field. The existing works on orchestration tools in TEL classrooms are reviewed to summarize their approaches and find the open issues to be addressed in the thesis.

Chapter 3 describes the need-finding study of the iterative design cycle. It gives the reader an overview of current challenges faced by teachers in the context of robot-mediated classrooms.

Chapter 4 illustrates the first stage of the iterative design of CelloRoom including the robot-mediated learning activities and the orchestration tool, reviews teachers' feedback and presents the final prototype elements. It brings CelloRoom to 6 classrooms across Switzerland and discusses the effectiveness of the tool, on the basis of objective and subjective data collected from 6 teachers and 91 students.

Chapter 5 closes the iterative design loop by evaluating the usage of CelloRoom 2.0 with a second round of studies, involving 5 teachers and 118 students, especially by looking at usefulness of CelloRoom 2.0 for supporting teachers' practices in orchestrating productive math discussions.

Chapter 6 describes the second round of need-finding study which gives the reader an overview of current challenges faced by teachers in orchestrating productive math discussions in the context of robot-mediated classrooms and proposes orchestration functionalities that can support teachers' needs in this regard.

Chapter 7 reviews the contributions of the thesis, summarizes the results of classroom experiments and provides directions for future works and the design of orchestration tools for ER.

2 Background and Related Works

2.1 Introduction

My research objective is to study the effect of classroom orchestration tools on teachers' orchestration routine in robot-mediated classrooms. This objective lies at the intersection of two research domains:

1. The context of the thesis is classrooms in which tabletop educational robots are used as learning technologies in collaborative and constructivist learning environments. I contribute to the literature in *Educational robotics* from a specific perspective of understanding teachers' challenges in using these robots in their classes and supporting them by designing orchestration tools.

2. My research aligns with answering teachers' needs by designing a classroom orchestration tool. Beside the implementation, an orchestration tool needs to be evaluated in terms of its usefulness and impact on teachers' orchestration routine. Therefore, this work also contributes to the domain of *orchestration of TEL classroom*.

3. This work also contributes to the literature of *Orchestrating Productive Math Discussion (OPMD)*, by exploring how teachers perform the practices of OPMD and proposing orchestration functionalities that can support teachers' needs to perform these practices,

In this chapter I review literature from the above mentioned domains, as it provides the ground for current research.

2.2 Table-Top ER in Classrooms

Research in ER and advances in the relevant technologies have produced commercial table-top robotic platforms able to meet the requirements and goals of educational settings (i.e., cheap, robust, easy-to-use) (Chevalier et al., 2016b) among which very successful products, such as LEGO Mindstorms, available worldwide (A. B. Williams, 2003) or Thymio robots largely adopted in schools in Switzerland and France (Riedo et al., 2013).

It's not a surprise that the first and still primary application of ER in education has been for learning robotic itself! For instance, LEGO Mindstorms (Fig. 2.1), as one of the most popular ER platforms, are used to teach the basics of robotic in project-based activities (Afari and Khine, 2017). Learners can practice different aspects of robotic (mechanics, electronics or programming), e.g. assembling, sensor calibration and running robot actuators, in project-based activities tailored to suit different educational levels, ranging from elementary school to universities (Mubin et al., 2013).

The breakthrough point for ER was introducing them for teaching programming. Robots can turn the output of the code on the screen into something more tangible, which is especially beneficial for novice programmers (Major et al., 2012). Moving from debugging in virtual environments to realistic scenarios (Magnenat et al., 2015), where even a perfect code can yield undesirable results due to real-world causes such as fluctuations in a sensor's reading (Ikeda and Szafir, 2021), enables learners to acquire a better feeling of the factors to take into account while coding. It was in the late 1980s that for the first time the LEGO/LOGO system (using the LOGO educational programming language with LEGO robots) became commercially available and was adopted by more than 15.000 elementary and middle schools in the United States (ÜÇGÜL, 2013). According to a very recent review of ER, LEGO robots are being used in close to half of all research efforts around ER (Lancheros-Cuesta and Fabregat, 2022).

After the success of LEGO robots, tens of robotic platforms were introduced for teaching programming at different levels (from novice to advanced) with different modalities for learner-robot-interaction, as illustrated in Fig. 2.2. For instance, for children aged 5-7 and novice to programming, Bee-Bot, a bee-shaped robot with several buttons on its back, enables children think like a programmer, especially by practicing sequencing skills (Papadakis and Kalogiannakis, 2022). As the next level, block-based programming can be used to program robots, like Thymio (Riedo et al., 2013), Sphero (M. Ioannou and Bratitsis, 2017), mBot (Pisarov, 2019), etc, which give students the ability to solve a variety of challenges, like following a line with the robot sensors or moving a robot inside a maze, to learn the basics of programming (Riedo et al., 2013).

Novel ERs, such as Ozobot (Fojtik, 2017), aim to give curriculum designers new possibilities for creating challenging robotic projects. For example, with Ozobot, learners can also program the robot based on a variety of underground paper colors (Fojtik, 2017). Similarly, while most platforms require virtual environments for programming, a recent research trend explores tangible interfaces, like Algorithmic bricks Kwon et al., 2012, for programming robots (Sa-

Figure 2.1: LEGO robots used for teaching robotic and programming. Left: assembling robots help children to learn the basics of robotic. Right: A group of children collaborating on a robot programming project.

pounidis and Demetriadis, 2016). The results of exploring the benefits of *Algorithmic bricks* on twenty-four elementary school students showed that this tangible programming interface is effective in enabling them to use logical thinking abilities to solve problems. Tangible interfaces provide a larger workspace for collaboration and a physical, concrete representation of the code (Marshall, 2007). The link between robots and programming languages is not limited to block-based programming languages and, at high school and university levels, includes the most common programming language in robotic (Vega and Cañas, 2019). In this context, the robots used are typically full-fledged manipulators (Gyebi et al., 2015; Qassem et al., 2010) or mobile robotic platforms (Araújo et al., 2015; Khamphroo et al., 2017).

The success of ER in teaching programming motivated researchers to explore the use of ER for teaching other curricular disciplines, and specifically addressing science, technology, engineering and math (STEM) topics in schools (Benitti, 2012). The typical approach to this goal has been to use already-existing ER, adapting them to the novel learning topic: Many of the ER used for programming started to be used in lessons for STEM-related curriculum (M. Ioannou and Bratitsis, 2017; Pisarov, 2019; Riedo et al., 2013). Indeed, robots are a good use case for demonstrating physics topics, such as velocity (M. Ioannou and Bratitsis, 2017), Newton's law of motion (D. C. Williams et al., 2007) and illustrating mathematics concepts, especially geometry-related topics (Brender et al., 2021).

As a special example, Cellulo robots (Özgür, Lemaignan, et al., 2017) were developed, as a

Figure 2.2: Learner-robot-interaction at different levels. Left: A child is programming Bee-bot with buttons to follow a straight line. Middle: a group of primary school students program the Thymio robot with visual block-based programming. Right: A group of university students program a robotic arm with advanced text-based programming languages.

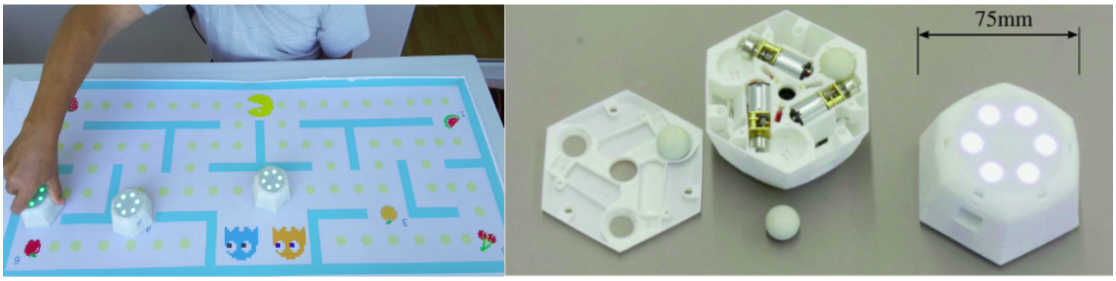


Figure 2.3: Left: Cellulo supports physical interaction through manipulation in different games. Right: Cellulo, a hexagon-shaped robot is equipped with three actuators to enable holonomic motion on a plane.

multi-purpose teaching tool, with the idea that a single robot could be used for designing a variety of different activities from Chemistry (Özgür, Lemaignan, et al., 2017) to mathematics (Khodr et al., 2020). Cellulo robots (Figure 2.3) are haptic-enabled, hand-held, hexagon-shaped robots, capable of holonomic motion. The key feature that makes the robot specifically interesting for learning activities is the absolute global localization (position and orientation (x,y,theta)) within an *augmented* paper sheet or maps which should be designed separately for each activity. When placed on the map, each robot can self-localize itself with sub-mm accuracy via an image sensor placed underneath the robot and send the data to a controller which could be a tablet or personal computer. By programming the Cellulo robots to behave based on their position on each map, in one activity they can be molecules that change their state of matter from solid to gas (Özgür, Lemaignan, et al., 2017) while in another activity they embody the X and Y coordinates to draw circles or lines with (Khodr et al., 2020). As shown in Figure 2.4, each learner would interact with one or more Cellulo by moving them or observing them move on the map, depending on the activity design.

Several studies have proven effectiveness of ER activities for improving students' collaboration (Khodr et al., 2020) and motivation to learn mathematics (Chin et al., 2014b). While ER is usually found useful to enhance learning (Khodr et al., 2020; Mitnik et al., 2008; D. C. Williams et al., 2007), literature also includes cases in which there was no improvement in learning (Hussain et al., 2006; Lindh and Holgersson, 2007). Limitations of research in ER, especially with new robotic platforms like Cellulo, include the limited focus on student-robot interaction, without considering teachers in the loop (Chin et al., 2014a; Mubin et al., 2013) and evaluating the class-level learning, i.e. the effect of using robots in teaching on students' learning. This is despite the importance of teachers' role in introducing technology to students as a reliable source (Benitti, 2012; Hughes, 2005).

2.2.1 Teachers & ER

The majority of teacher-oriented ER researches have focused on supporting teachers outside of the classrooms by enhancing teacher professional development or teacher training (Chevalier et al., 2016b; El-Hamamsy et al., 2021; Khanlari, 2016). Researchers have gathered teachers'

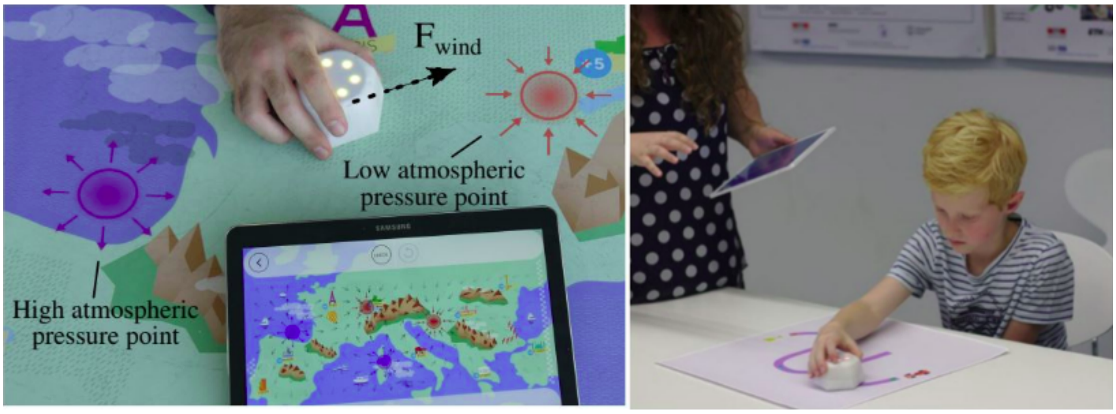


Figure 2.4: Cellulo robots can be used for a diverse range of activities. Left: In the Windfield learning activity for physics, Cellulo lets learner haptically feel how winds are formed by differences between high and low pressure points. Right: in a handwriting activity, Cellulo enables learners to *feel* the shape of the letters.

opinions about the applicability range of robots in various domains, their motivation and challenges to use ER in teaching (Chevalier et al., 2016b; Khanlari, 2016). Studies indicate that teachers found robots most useful for teaching mathematics and science and also for practicing collaboration and engaging students in after-lesson reflective process (Chevalier et al., 2016b). When teachers were asked about their challenges with robots in classrooms, they mentioned the lack of connection with the educational curriculum as one of the main ones (Alimisis, 2013; Mubin et al., 2013). Another challenge, as important as the previous one, is difficulty of having to deal with technical complexity of robotic classrooms (Mubin et al., 2013); numerous questions about robots from students on one side and the teachers' fear of technical failures can indeed overload teachers' management capacity (Khanlari, 2016).

Although the majority of the above-mentioned research has been performed in large scales studies (for instance involving 200 teachers in Switzerland (Chevalier et al., 2016b) and 201 teachers in Greece (Papadakis et al., 2021)), their research methodologies are mostly limited to gathering information through surveys (Papadakis et al., 2021) or group discussions (Chevalier et al., 2016b) which do not capture the full picture of what's going on in the classrooms. For instance, Chevalier et al., 2016b concluded that there should be some difficulties that teachers face having Thymio robots in the real conditions that surveys and group discussions cannot capture, thus requiring in-session studies of teachers' behaviour to be fully understood.

2.2.2 Orchestration Tools designed for Robot-mediated Classrooms

Few research has attempted to design orchestration tools for robot-mediated classrooms. These works typically focus on finding indicators or predictors of the students' progress during robot-mediated activities that teachers can access and use in real-time. For instance, Orlando et al have used educational data mining (Orlando et al., 2020) to calculate students' scores in a robotic activity and created an orchestration tool to show this information to teachers. In a similar research, Jormanainen, 2013 conducted his doctoral research to address teachers' problem regarding the intrinsic nature of unpredictable events in open-ended ER activities. He tried to support teachers in an ER programming activity by classifying the students' performance status into four categories (indicated by colors from green to red) using decision trees as classification method. These studies emphasized the importance of showing students' progress in a robotic activity to teachers having unpredictable paths in students' activities.

2.3 TEL Classroom Orchestration model

A significant part of research on TEL classroom orchestration has tried to model how teachers orchestrate their classrooms in different contexts, based on observing teachers' behaviours (Dillenbourg, 2013; Phiri et al., 2016; Prieto et al., 2011). A well-known model in the literature, dedicated to TEL classrooms, has been proposed by Prieto et al., 2011 and characterizes classroom orchestration by five main aspects. Since this thesis builds on this model, in this section we briefly revise it:

2.3.1 Design/planning

The process of orchestration starts before the class by planning the learning activities that are supposed to be coordinated during class time (Prieto et al., 2011). Depending on the learning technology, the lesson should be designed according to the capabilities of the underlying learning technology, so that the learning goal would be achieved (Prieto et al., 2011). Here the challenge remains that technologies come from researchers while the task of lecture planning and coordination falls on teachers, thus creating possible mismatches between the learning technologies and the learning goals (Do, 2012). To this end, studies suggest collaboration between researchers and teachers to design rich learning activities (Lin and Van Brummelen, 2021), so that both parties benefit from the interaction with the other and learning technologies and lectures using them are designed in synergy, as the result of the collaboration.

2.3.2 Management

An important part of teaching includes managing class resources, most importantly managing time, activity-flow, group activity and technical resources. Time constraints are the most important limit for teachers, since time management correlates directly with the quality of classroom orchestration (Prieto et al., 2011). A well-orchestrated lesson is when teachers have flexibility of managing the sequence of the activities (Dillenbourg and Jermann, 2010). The activity management can be performed through routine social interactions in the classroom or in a *computerized* way. In the computerized mode, the learning activities and students' information are computer-interpretable scripts, so that the system is able to assign the activities/groups by teachers' authorization (Haklev et al., 2017) or in an automated intelligent way (Olsen, 2017).

Group management becomes important in Computer-Supported Collaborative Learning (CSCL) settings. Teachers have to assign students to groups and make sure the group work is fruitful and flowing smoothly throughout the session (Olsen, 2017). There could be barriers in collaboration that require teachers' attention, like students' disagreement on a shared solution especially in open-ended problem solving, or when the workload is not shared equally among the group members (Prieto et al., 2015).

As TEL classrooms are equipped with new technologies, part of orchestration is devoted to managing the learning technologies in classroom (Dillenbourg and Jermann, 2010). This requires teachers to perform some technology-related tasks, for instance, if the technology needs some sort of preparation (like charging before the session), checking if students are logged in, distributing the devices among students, dealing with technical failures, etc (Dillenbourg and Jermann, 2010). Although the task itself is not a complex process, it will magnify at the class level; a simple login process could be easily followed by students' questions which wastes considerable part of class time (Dillenbourg et al., 2011).

2.3.3 Adaptation

One of similarities between teaching and Jazz orchestration is the act of changing/adapting the script *on the fly* according to the audience (students) (Dillenbourg, 2013). According to Prieto et al., 2011, teachers need to change and adapt the design/plan, like adding/ skipping exercises, changing the difficulty level to both the learning goal of the classroom and the emergent occurrences during the enactment of learning activities, for example a learning activity taking much more time than what was planned or the learning technology not working. Similar to management, the adaptation can be done either through teacher-student-communication or through technological systems (Amarasinghe et al., 2020; Haklev et al., 2017). More importantly, teachers need to make the right decisions at the right moment to adapt the activity sequence. For example, if eighty percent of the class has finished an activity should the teacher wait for the rest to finish or proceed to the next activity? (Dillenbourg and Jermann, 2010). In this matter, automated tools can be helpful by predicting the timeline of students' performance (Faucon et al., 2020).

2.3.4 Awareness

Taking orchestration actions requires being aware of what is happening in the classroom. Awareness is not necessarily about deep-level student modeling, rather it serves to provide indicators of the students' progress in the activity (Dillenbourg, 2013). Each teacher might have their own way of monitoring the classroom, some do so by going around and visiting students, others by far monitoring or *reading the classroom* (Holstein et al., 2017). Bringing learning technologies to classrooms can cause difficulties for the routine awareness mechanism teachers choose. For example, in classrooms with screen-based learning technologies, teachers often complain about how the screens constitute a barrier preventing them to see what the students are doing, and thus affecting their monitoring routine (Holstein, 2019).

Awareness is not limited to teachers' knowledge about students, but it also includes teachers' needs to be aware of their own teaching process. For instance, in student-centered learning environments, it is important that a teacher reflects on students' participation in class talks or *classroom discourse* to make sure that the teacher is not the sole talker (Prieto et al., 2020). This awareness could arise at the same time when the teacher is enacting the learning activities, for example by knowing their proximity to students' desks (known as reflection-in-action) (An et al., 2018) or later on, by reading a visual report of the class main events or class timeline (reflection-on-action) (Prieto et al., 2020).

2.3.5 Role of Teacher and Other Actors

Although it might seem that it is teachers that should carry all the orchestration workload, all the above-mentioned concepts presented here can be performed by learners or an automated system, lifting the orchestration load from teachers' shoulders. Especially in student-driven or constructivist learning environments, researchers argue that teachers should act as *facilitators*, rather than as a knowledge source (Prieto et al., 2011). Therefore learners can take more responsibility, for example by reporting their progress. Also, automated systems can offload teachers of some tasks, thus enabling them to focus on other, high-priority ones. For example, FROG (Haklev et al., 2017), an orchestration tool for scripting online learning activities, can automatically pair students in groups according to various collaboration scripts that teachers might want to implement (like jigsaw (Stasko et al., 2008), argue-graph (Dillenbourg et al., 2011)), based on automated analysis of students' learning profile.

2.4 Orchestrating Productive Mathematical Discussion

Whole-class discussions are an essential part of constructivist teaching that normally happen in three sequential phases (Lampert, 2001):

1. **Introduction phase** in which teachers introduce the problem to students, what activities are they supposed to do and what outputs are expected.

2. **Exploration phase** in which students work on the given activities and teachers provide guidance to ensure the correct flow of the activities.

3. **Whole-class discussion** during which various students' solutions in the activities are supposed to be discussed. Open-ended questions such as "How was the activity? Was it

easy?" are typically used by teachers as a starting point of the discussions. (Evans and Dawson, 2017)

According to the PS-I (Problem-Solving followed by Instruction) theory (Sinha and Kapur, 2021), once students have acquired enough experience on the learning activity, class discussions can be given about the learning goal to connect the students' experiences with the activities to their underlying learning goal. Such discussions require teachers to *orchestrate* them by aggregating the students' reflections on their activity, to identify new ideas from the students' works and build the target concept on the students' works (Evans and Dawson, 2017; Kriz, 2010).

Productive discussions have been especially beneficial in the mathematics classroom, where the open learning tasks are cognitively challenging (McCormick and Donato, 2000) and mathematical discussions become an integral part of effective teachers' practices. Researchers have identified key practices that could lead to orchestrating productive discussions (Dunning, 2022; Michaels and O'Connor, 2015; Stein et al., 2008): one of the most-cited frameworks in this regard is proposed by Stein et al. (Stein et al., 2008). This framework (called "Orchestration of Productive Mathematical Discussion" (OPMD) framework) proposes five sequential practices, of which four specifically target teachers' actions in class-time (while the other one involves teachers' actions outside of the class discussion moment, and is thus not considered in this study). The four practices are as follows:

1. **Monitoring students' mathematical thinking** on the activities *during* the exploration phase: while monitoring in Prieto et al.'s orchestration framework (Prieto et al., 2011) generally concerns awareness of students' progress in the learning activities (e.g. noting how many students are involved in the learning activity), monitoring in Stein's framework exclusively concerns on students' responses that involve mathematical thinking. The goal of monitoring is to identify the mathematical learning potential of particular strategies that students use.

2. The teacher should **select particular students' solutions** to be shared with the rest of the class by calling on students, with the intention of having specific mathematical content being raised in class discussions.

3. The teacher should **purposefully sequence** the order in which selected students' solutions are shared, with a rationale to connect them one another. The goal is to maximize the chances of surfacing terms related to the mathematical lesson goals. As an example, teachers might first share the strategy used by the majority of students, which might not be effective. Later, by comparing to other solutions, the teacher can have a better strategy for emerging math-related ideas.

4. Finally, the teacher should help students **make connections** between the mathematical ideas that are reflected in the selecting and sequencing practices and the underlying

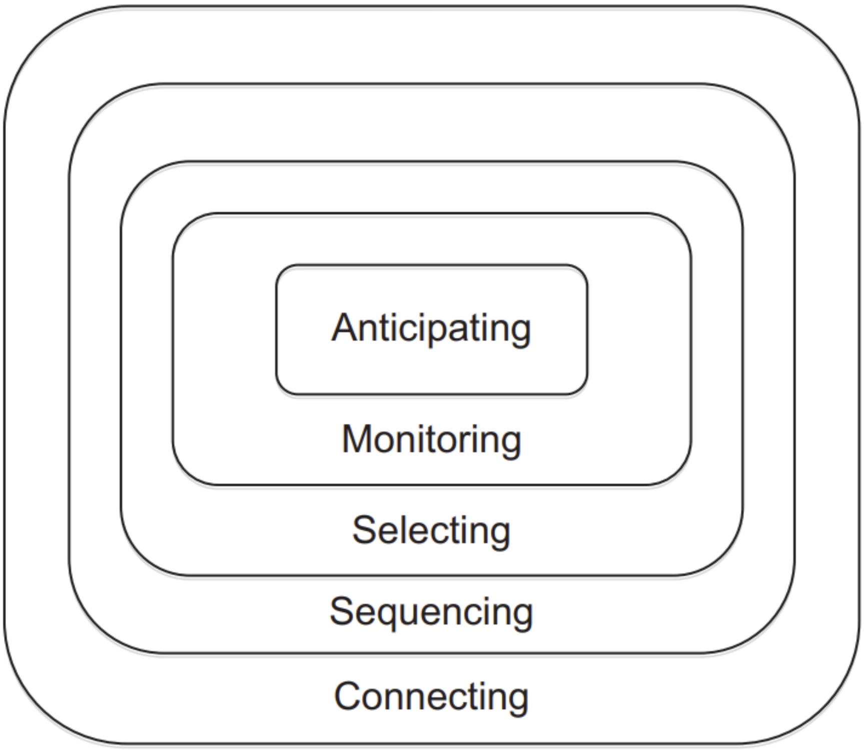


Figure 2.5: A schematic diagram of the five practices in *Orchestrating Productive Mathematical Discussion*. Each practice is in a sequence with respect to others. *Note: Image taken from (Stein et al., 2008)*

> mathematical goals. The goal is to have the students' presentations build on each other to develop mathematical ideas. The art of productive orchestration implies that rather than simply choosing pre-defined solutions as being correct, students' responses should be developed and then build on each other collectively (Fennema et al., 1996).

Researchers have used this framework extensively to evaluate the role of these practices in the classroom, for example by helping teachers plan their class discussions (Larsson, 2015) or evaluating how they played out in real class-time (Criswell and Rushton, 2012; Tyminski et al., 2014). Orchestrating discussion productively is one of the criteria that distinguishes novice and expert teachers (Evans and Dawson, 2017). The main challenge for teachers is that the discussion should be based on the students' contributions which requires *real-time data* from students' interaction with the learning system (Do-Lenh et al., 2012). Teachers find it challenging to select the *best* samples of students' works to be shared *in-the-moment* due to different and unanticipated students' approaches (Stein et al., 2008). The teacher has to let students share their ideas at the same time ensuring that the emergence of the core mathematical goals happens within class time (Evans and Dawson, 2017).

Research suggests that orchestration tools, containing students' responses to quizzes or their activity traces (Peddycord-Liu et al., 2019), could potentially be helpful to create class discussions (Amarasinghe et al., 2022; Do-Lenh et al., 2012; Fong et al., 2013; Hatch et al., 2011; Hayashi et al., 2019). Orchestration tools have also shown advantages for the teaching process by providing equitable at-a-glance access to students' information (Fong et al., 2013) and facilitating the assessment of students' learning in the classroom (Hayashi et al., 2019). Several studies have shown their benefits for the learning process, including engaging students (Fong et al., 2013) or increasing learning gain (Hatch et al., 2011). As an example, NumberNet, a network of multi-touch tablet-tops and a student-facing dashboard, was developed by Hatch et al. (Hatch et al., 2011) for teachers in the context of an upper primary school. Teachers could project a group's activity on the beamer, which can potentially be helpful for the selecting practice, and move the students' solutions among groups (allowing for making connection between students' presentation (sequencing)), so they can learn from each other. The results of a pilot study, including two teachers orchestrating math activities with NumberNet, showed an increase in the number of calculations by students. Although these works discuss the benefits of sharing students' solutions via orchestration tools for class discussion, they only have focused on the end-effects (e.g. whether the presence of the tool has a positive effect on students' engagement (Do, 2012)) while I argue that it's also necessary to explore teachers' usage of the tool and see whether it matches the practices of OPMD. Only with complete understanding of how teachers use the data on orchestration tools during class time, it would be possible to provide design guidelines for orchestration tools that can fully support teachers in OPMD.

2.5 Classroom Orchestration Tools

In this section, we present an overview of several orchestration tools in the literature that motivate and guide the design process of the proposed orchestration tool in this thesis. Although considering all the orchestration tools in literature is beyond this research, however my focus has been on the tools, such that: 1) these tools have evaluated their effectiveness in empirical studies (since this is the goal of this thesis) 2) the literature review covers a breadth of contexts in which orchestration tools have been used; e.g. school and higher education, classroom and online settings, individual and collaborative learning using different devices as the orchestration tools. Researchers have used different terminology for what we call here orchestration tools, such as learning dashboards (Martinez-Maldonado, 2019), orchestration tools (Amarasinghe et al., 2020) or teacher augmentation tools (An et al., 2020), however as they all aim at supporting teachers in real-time class management, for simplicity we refer to them as orchestration tools throughout the rest of this thesis.

Commercial in-the-market learning management tools have already started to include orchestration tools in their services, like Moodle (Rice and William, 2006) or Desmos (Ebert, 2014) with basic features like showing students' progress. At the same time, research on orchestration tools has tried to evaluate their usefulness and application in authentic classrooms. Such studies can be found in the literature across a range of disciplines, including HCI (An et al., 2020; Sellier and An, 2020), AI for education (Feng and Heffernan, 2006; Holstein, McLaren, et al., 2018), learning analytics (Holstein et al., 2019; Mavrikis et al., 2016) and learning sciences (Amarasinghe et al., 2020; Tissenbaum et al., 2016). Orchestration tools can be in various forms, such as web/mobile interfaces (Amarasinghe et al., 2020; Hatch et al., 2011; Martinez-Maldonado et al., 2013), distributed displays (Alavi et al., 2009; Bakker et al., 2013; Balestrini et al., 2013) or wearable tools (Balestrini et al., 2013; Holstein, 2019). Table. 2.1 summarizes the context information about the selected orchestration tools in literature to review in this Chapter. According to Table 2.1 and the literature reviews on the matter (Schwendimann et al., 2016), research in orchestration tools has been performed over a variety of educational levels: from primary (Bakker et al., 2013; Caballero et al., 2014) to secondary and high school (Balestrini et al., 2013; Holstein, McLaren, et al., 2018), universities (Amarasinghe et al., 2020; Gerard and Linn, 2016; Martinez-Maldonado et al., 2013) and even vocational schools (Do, 2012). Orchestration tools have been used in knowledge inquiry tasks, for example, to create concept maps (Willerman and Mac Harg, 1991) to teach topics in mathematics (Hatch et al., 2011; Olsen, 2017; Swidan et al., 2019) or, less commonly, social sciences (Fong and Slotta, 2018; Martinez-Maldonado et al., 2013). In these studies, students typically use a screen-based learning technology, like multi-touch interfaces (Caballero et al., 2014; Granda et al., 2015; Hatch et al., 2011; Martinez-Maldonado et al., 2013), tablet (Fong and Slotta, 2018; Hayashi et al., 2019) or personal computer in classroom (Deeb et al., 2018; Swidan et al., 2019). Each of these tools has a main functionality which is summarized in Table 2.1.

2.5.1 Four Examples of Orchestration Tools

Prior to designing any orchestration tool, studying teachers' needs in the specific context that the tool is aiming to assist them in is counted as a necessary practice, since each orchestration tool would be designed to address specific teacher's needs in a certain context (Holstein et al., 2017). When reviewing the literature on orchestration tools that might be relevant to our context, the four important characteristics of robot-mediated classrooms, which arose from the studies reported in Chapter 1 of this thesis should be considered: 1) they are mostly being performed in collaborative settings 2) they constructivist learning environments 3) they are used for teaching STEM related topics, especially mathematics and physics and 4) learners are mostly in the age range of primary schools. According to these criteria, below, we briefly introduce the four most relevant orchestration tools, since in each case, one of the above mentioned specific features is shared with robot-mediated classrooms. In brief, MTDashboard was designed for multi-tabletop classes in which students *collaboratively* engage in the learning activities. The second case study is classroom with Tinkerlamp where the goal is to teach in a *constructivist* learning environment. Lumilo is a well-known orchestration tool in literature used for teaching *mathematics*. Lastly, Firefiles was extensively tested in *primary schools* with students in the age range of 6-9 years old.

Case 1: MTDashboard, an orchestration tool for multi-tabletop classrooms.

In the context of a multi-tabletop classroom, Martinez Maldonado, Dimitriadis, et al., 2012

Table 2.1: The contextual information about the selected orchestration tools in the literature, according to the two criteria mentioned in Section 2.5.

	Main Functionality	**Educational Context**	**Learning Technology**	**Learning Topic**	**Related Orchestration Aspect (Prieto et al., 2011)**
Lantern (Alavi et al., 2009)	Display students' work progress, help-requests	in-person University	Pen and paper	Programming	Awareness
Pyramid App (Amarasinghe et al., 2020)	Activity flow control	in-person University	Tablet/personal computer	Open-ended knowledge sharing tasks	Adaptation
Signal Orchestration System (Balestrini et al., 2013)	Wearable showing student's roles in groups	in-person Secondary school	Pen and paper	Citizenship and Human Rights	Management
FireFlies (Bakker et al., 2013)	Providing nonverbal teacher-student communication channels	in-person Primary school	Pen and paper	General	Management
Single Display Groupware (SDG) (Caballero et al., 2014)	Aggregated students' artefacts	in-person Primary school	Shared large screen	Geometry	Awareness
Spinoza (Deeb et al., 2018)	Automated group formation	in-person University	Personal Computer	Programming	Management
TinkerBoard (Do, 2012)	Visualizing students' artefacts	in-person Vocational school	Table-top simulation system	Logistics	Awareness
Common Knowledge (Fong and Slotta, 2018)	Visualizing students' ideas	in-person Primary school	Tablet	Biodiversity	Awareness
MT Dashboard (Granda et al., 2015)	Visualizing students' participation	in-person University	Multi-tabletop	Software design	Awareness, management
Gerard and Linn, 2016	Automated alert on students' essay quality	in-person Secondary school	Personal Computer	Photosynthesis	Awareness
Kit-Build concept map (Hayashi et al., 2019)	Aggregated visualization of groups works	in-person Secondary school	Tablet computers	Knowledge inquiry	Awareness
NumberNet (Hatch et al., 2011)	Project a group activity on the whiteboard	in-person Primary school	Multi-touch tablet	Mathematics	Awareness
Lumilo (Holstein et al., 2019)	Automated augmented visualization of students status	in-person Secondary school	Intelligent tutoring system	Mathematics	Awareness
MTDashboard (Martinez-Maldonado et al., 2013)	Visualizing collaboration quality	in-person University	Multi-touch table-top	Management and Organisational Ethics	Awareness
SAGLET (Swidan et al., 2019)	Alerts on group critical moments	Online Secondary school	Personal Computer	Geometry	Management

Figure 2.6: MTclassroom (Martinez-Maldonado et al., 2013): learners are collaboratively performing a problem-solving task. The teacher is monitoring groups with the aid of MTDashboard to track their collaboration quality. *Note: Image taken from Martinez-Maldonado et al., 2013.*

used class-observation and interviews with teachers to discover teachers' needs for managing equality in students' collaboration. Based on these observations, they developed an orchestration tool called *MTDashboard* that includes a "Radar of Physical Participation". This indicator shows teachers the number of touches on the tabletop per student to gauge students' collaboration quality (Martinez-Maldonado et al., 2013), which helps teachers prioritize the group who may need attention.

MTDashboard, as shown in Fig. 2.7, is designed to capture students' interactions working in collaborative activities in MTclassrooms. Each MTclassroom, shown in Fig. 2.6, consists of four interactive tabletops, one or more vertical public displays and a MTDashboard. MTclassrooms are similar to robot-mediated classrooms where in both cases, multiple groups of learners are engaged with the learning activity including the related technology (robot/table-top tablet) and the teacher is orchestration the learning progress. Researchers (Martinez-Maldonado et al., 2013) experimented this setting in two teaching periods for two university level topics. The results of those studies confirmed that teachers value indicators of group work and individual participation in group activity, especially for post-hoc analysis, specifically appreciating the information about the quality of the students' works in the collaboration.

Case 2: TinkerBoard, an orchestration tool in the form of public display

TinkerBoard (Do, 2012) was designed in the context of training apprentices for learning logistics in vocational schools across Switzerland. Do, 2012 designed TinkerLamp, a tangible tabletop simulation system that makes the mathematical abstract complex concepts tangible for students. After the first trials, via classroom observations, researchers realized that although the system was successful in making students engaged in the learning activities, teachers needed to make students reflect more on their design before running the simulation (Do-Lenh et al., 2012). In regards to the learning system and activity, classrooms with TinkerLamp are

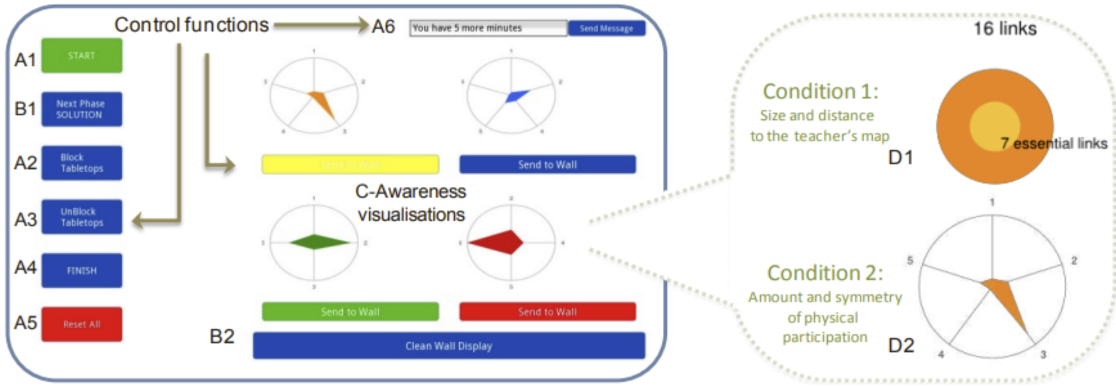


Figure 2.7: User interface of the MTDashboard (Martinez-Maldonado et al., 2013): on the left side the teacher has the control functions (e.g. start/end the activity sequence). The information about collaboration quality is visualized on the dashboard for each group with a radar chart. *Note: Image taken from Martinez-Maldonado et al., 2013.*

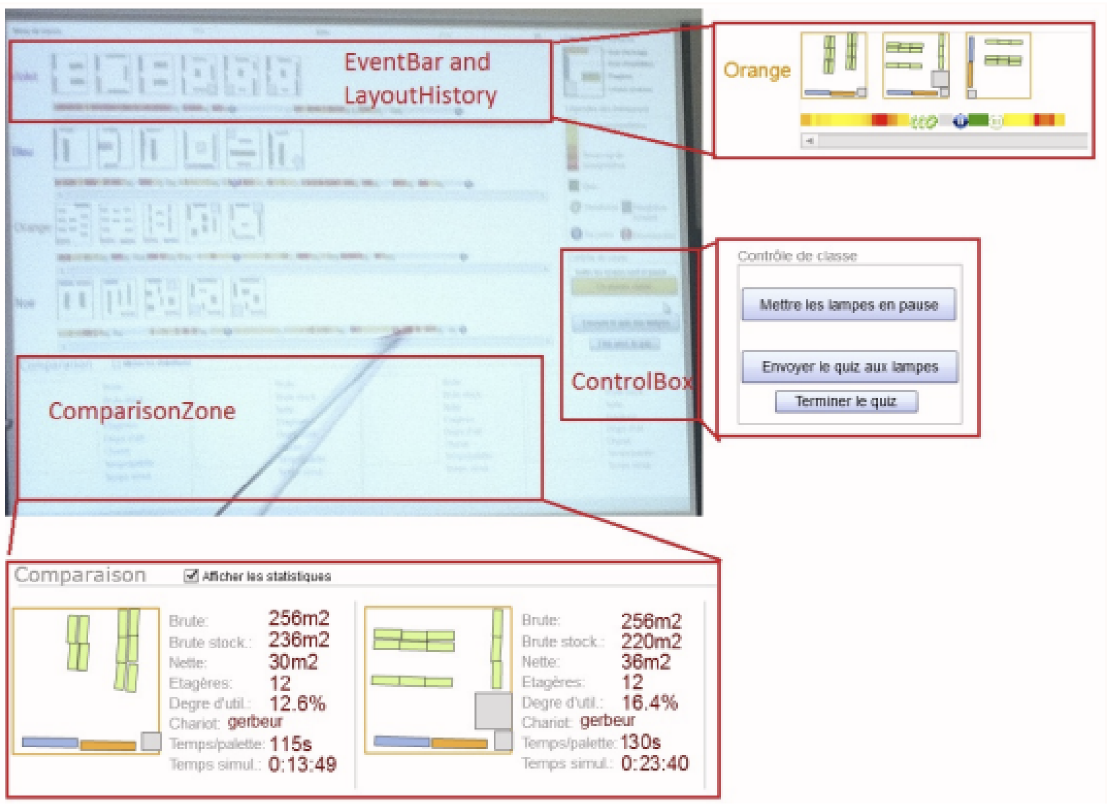


Figure 2.8: TinkerBoard: Summarizes the students' simulations in an aggregated form for teachers. Each group's activity history and most critical events are shown by the *layout history* and *event-bar*. Teachers can compare two groups' simulations for creating class discussions. *Note: Image taken from Do, 2012.*

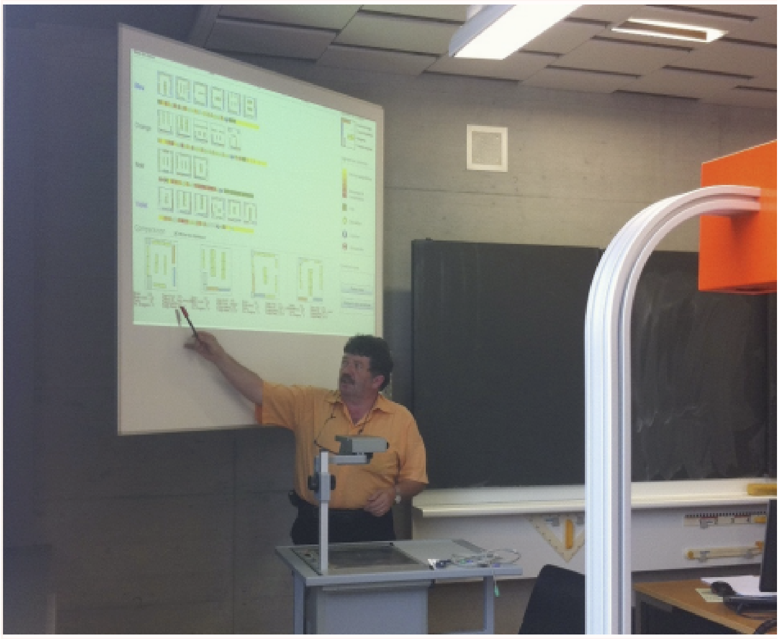


Figure 2.9: A teacher using TinkerBoard to create class discussion by referring to a group's simulation history. *Note: Image taken from Do, 2012.*

similar to the ER activities, since in both cases, teachers orchestrate a constructivist learning environment where learners have to engage with the activity (robot-mediated activity or simulation with TinkerLmap) and afterwards its teachers' role to connect he earning activities to its learning goal in form of class discussion. To address this challenge, they designed two orchestration mechanism that could potentially address the issue:

1. TinkerBoard, a public learning dashboard as shown in Fig. 2.8, was added to the system to provide aggregated views of all the students' solutions, so that the teacher was able to compare students' simulations, leading them to reflect on their experience, as shown in Fig. 2.9. Using Tinkerboard led to a more engaged classroom atmosphere and better learning gain, compared to the control group. TinkerBoard showed that debriefing moments are enhanced by the presence of a student-facing dashboard (Do, 2012).

2. Another beneficial orchestration mechanism that was added to this context is a pausing feature (authority to control the progression of the activity), called TinkerKey, enabling the teacher to stop the groups that were repeatedly running the simulation without enough reflection or falling in the *manipulation temptation* (Do-Lenh et al., 2012). Using the TinkerKey led to increase students' reflection in groups (Do, 2012).

Case 3: Lumilo, an orchestration tool in the form of smart glasses

In the context of face-to-face classrooms with intelligent tutoring systems, Holstein (Holstein et al., 2017) found that the lack of monitoring capabilities in AI tutoring systems has been a

Figure 2.10: Lumilo (Holstein, McLaren, et al., 2018) in classroom: Left: An illustration of how Lumilo projects students' progress status as floating icons over their heads. Right: Lumilo can also show the areas students are struggling within. *Note: Image taken from Holstein et al., 2019.*

reason for making teachers feel out of the loop and consequently lose motivation towards using them in class. In a later study, through an iterative series of participatory design and field studies in K-12 classrooms, he discovered that another difficulty for teachers in this context is inequity to allocate their time across students (Holstein et al., 2017). The process of addressing these difficulties led to creation of *Lumilo*. Researchers specifically designed Lumilo for teaching mathematics, which makes it necessary to review their results, as a significant percentage of robot-mediated activities are STEM related and specifically are used for teaching mathematics (Mubin et al., 2013).

Lumilo (Holstein et al., 2017) is an augmented- reality based orchestration tool, in the format of mixed-reality smart glasses for teachers in AI-supported K-12 classrooms (shown in Fig. 2.11). Lumilo augmented the teachers' awareness of students' learning status with visual or sonic notifications. Students' status was shown as mixed reality icons (e.g., emoji or question marks) floating above individual students' heads in real-time, computed using learning analytic methods, as shown in Fig. 2.10. Lumilo was designed to alert teachers about situations that the AI tutor cannot be helpful in (e.g., an icon appears over a student's head if the AI tutor finds its attempts to help a student unsuccessful). Lumilo can also show which areas students are struggling with, along with examples of specific errors the students have made, as shown in Fig. 2.10. The results of multiple field experiments showed that using Lumilo could effectively change teachers' priority of visiting students in need for help (Holstein, 2019).

Case 4: FireFlies, a distributed orchestration tool

By studying the dynamic nature of teachers' in-session behaviours, researchers realized teachers' need to continue their classroom routine without being interrupted by the orchestration tools (An et al., 2017). They found that teachers' priority is to assess students' status and attend to their needs, which suggests that the orchestration tool needs to provide them with awareness information without distracting their attention from students. FireFlies (Bakker, van den Hoven, and Eggen, 2012) attempts to mediate between these two goals by relying on lamps distributed on students' desks which are pre-programmable for different applications. The interesting fact is the context in which researchers performed their experiments: primary school classrooms which are a less-touched context in researchers on orchestration tools (Schwendimann et al., 2016), while most ER activities are happening in this educational level (Mubin et al., 2013). One application, called ClassBeacons, enhanced teachers' reflection-in-action by showing how a teacher divides his/her time over students' desks during a class session, based on real-time positioning data (Sellier and An, 2020). Teachers could thus prioritize their next visit, according to the color of lights around the class.

Such distributed orchestration tools have been found to be particularly helpful when students are using screen-based activities, like virtual learning environment. In another example, called FireFlies-VLE (d'Anjou et al., 2019), each lamp showed students' progress in an online activity, mapped to a purple–blue color spectrum. FireFlies-VLE offered an overview of each student's progress without requiring teachers to go and closely check their screens. A field deployment showed that using the system led teachers to distribute their teaching time more efficiently across different groups, depending on their progress in the activities.

An interesting factor in this study is that while ninety-five percent of students perceived the system positively, it was only thanks to the qualitative data that researchers found out that FireFlies is only acceptable by students if there is no stigmatizing effects (they don't feel they are labeled) (d'Anjou et al., 2019). This observation is an example of the importance of qualitative analyses, which can provide key insights not attainable via quantitative analyses.

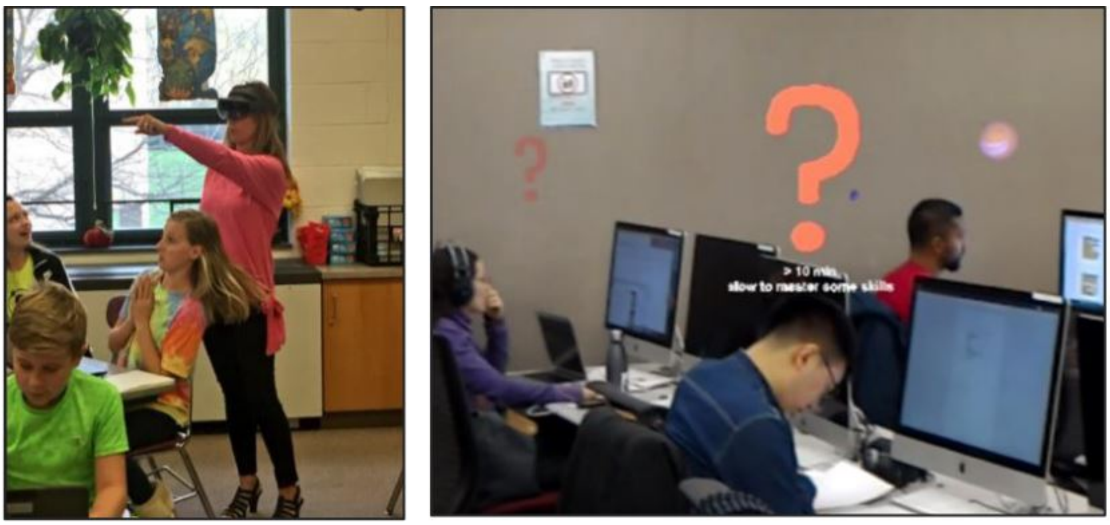


Figure 2.11: Left: A teacher using Lumilo in a class. Right: A student in need of help is indicated by a question mark on Lumilo. *Note: Image taken from Holstein et al., 2019.*

Figure 2.12: Examples of distributed orchestration tools: Two different implementations of the FireFlies platform. Left: *ClassBeacons* (Sellier and An, 2020) for collaborative problem-solving activities. Right: *FireFlies-VLE* (d'Anjou et al., 2019) for individual virtual activities. *Note: Image taken from d'Anjou et al., 2019; Sellier and An, 2020.*

2.5.2 TA Framework: A Design Space for Orchestration Tools

As we have seen in Section 2.5, there is a large number and variety of orchestration tools in literature. To characterize these tools, An et al., 2020 have proposed a framework, named TA framework , which proposes a five-dimensional design space for orchestration tools.

1. **Target**

   In terms of the content of the orchestration tools (i.e., the information they represent or the functionalities they provide for teachers), the TA framework mentions a range of *perception* (what to notice) to *action* (what to act upon) functionalities.

   Perception Teachers would *perceive* visualizations of students' activity traces in two ways:

   (a) Progress-based data (e.g. informing about students' pace and the time spent on the activities Faucon et al., 2020) help teachers have an aggregated view of class progress.

   (b) Artefact-related data (e.g. students' artifacts in game-based environments (Caballero et al., 2014; Hatch et al., 2011) or knowledge inquiry Fong and Slotta, 2018; Swidan et al., 2019, their answers to quizzes (Verbert et al., 2013), etc) provide more detailed information about students' progress comparing to the progress-related data .

   Alert In the middle of the range, there is information, generally in the format of *alerts*, directly helping teachers to prioritize their actions. For instance, tools can help teachers to optimize their group visits by providing indicators, like collaboration indicators in MTDashboard (Martinez-Maldonado et al., 2013), automated assessment of students' works (Gerard and Linn, 2016; Swidan et al., 2019), information about teachers' proximity and time distribution among students (An et al., 2018). *Advising* orchestration tools provide *recommendation* for teachers to make a certain decision, like the moment to transit between activities (Olsen, 2017) or the next potential group to visit (Martinez-Maldonado et al., 2014a) and group formation (Deeb et al., 2018).

Action In addition to augmenting teachers' awareness, orchestration functionalities can advise or facilitate teachers to take actions in classrooms and have control of the activity flow. The most commonly implemented actions in orchestration tools are the ability to control the activity flow (start/stop/pause the activity), decide to project students' artefacts on the board and changing the difficulty level of the activities (Amarasinghe et al., 2020). The orchestration actions can be performed from an individual level (e.g., providing help to a student facing a particular issue) to a class-wide level (e.g. sending a message to all groups (Martinez-Maldonado et al., 2014a)). For instance, a teacher might want to pause students' activity through controlling the learning technology in different scenarios: in one scenario, a teacher wants to focus the attention of the *whole class* onto a specific point, while in another scenario the teacher wants to provide meta-cognitive support for *a specific group* who is doing too many simulations without reflection (Do, 2012).

2. **Attention**

   Orchestration tools can be distributed in the classroom over the students' desks, like FireFlies (Bakker et al., 2013) and Lantern (Alavi et al., 2009). In this way, the orchestration tool requires little effort from teachers to get the information. Supporting this idea, in early need-finding studies related to developing Lumilo, teachers emphasized that much of the information they take during a class session comes from *"reading the classroom"* (Holstein, 2019). One of the benefits of Lumilo was that for using it, teachers did not need to get away from the class. In a similar way, systems such as CawClock (Bakker, van den Hoven, Eggen, and Overbeeke, 2012) use soundscapes to help teachers manage their time over groups.

   On the other hand, in most tablet or web-based orchestration tools, like FROG (Haklev et al., 2017) or Pyramid Dashboard (Amarasinghe et al., 2020), teachers need to focus their attention to use the orchestration tool. They might have to get away from the class at least for a few seconds, since processing those information requires special attention from teachers. These tools become more useful when there is a significant amount of data that requires to be visualized, so teachers need a rich separate interface for interpreting it (Granda et al., 2015). Another use-case is when teachers want to share information with students by projecting it on a beamer (Caballero et al., 2014; Do, 2012; Hatch et al., 2011). In the latter case, the whole class attention is devoted to the tool.

3. **Social Visibility**

   With tablet/PC based orchestration tools, the data is only provided for teachers privately, for example in Lumilo (Fig. 2.11) it's only the teacher who can see the students' progress status (Holstein et al., 2017). Another example is group's collaboration quality, shown on a tablet in MTDashboard (Martinez-Maldonado et al., 2014a). This is especially useful when teachers don't want to share groups' information with the students because of different reasons, for example not making students feel to be in competition with each other. At the same time, sharing the information about students' artefacts in their activities can be useful to inspire reflections on their progress (Caballero et al., 2014). In this case, teachers would share these data but *selectively*. In distributed systems, like FireFlies (Bakker et al., 2013) or Signal Orchestration Systems (Balestrini et al., 2013) the information is always openly available to all students, however the type of information shared is carefully chosen to be something neutral rather than a metric that ranks students with respect to each other, to avoid them feeling judged by the system (Bakker et al., 2013).

4. **Presence over Time**

   Tools can be present continuously in the class, like distributed tools (Signal Orchestration System (Balestrini et al., 2013)) or public displays (e.g. Single Display Groupware (Caballero et al., 2014)). In this case, teachers can access it without any effort, for example, teachers could look anytime at the tool (Fong and Slotta, 2018) while helping a particular learner team. On the other side, tools could also only be visible when teachers want (also called as selective awareness), like the floating icons over students' heads in Lumilo (Holstein, 2019).

   A design challenge here is to support teachers' awareness of class events by providing them with relevant information via the orchestration tool, at the same time ensuring that such information do not distract them from paying attention to the students and the teacher-student communication (An et al., 2020). The advantage of the tools that present information continuously is being easy to interact with, however for time-critical phenomena, like a mis-usage of the learning system (Martinez-Maldonado et al., 2014a), teachers need to be notified as soon as possible. In the latter case, using selective awareness, like wearable tools (Balestrini et al., 2013) or alert functionalities (Swidan et al., 2019) is especially helpful in prioritizing their attention or intervention in-the-moment (An et al., 2020).

5. **Interpretation**

   Orchestration tools can simply show the raw data, for example in TinkerBoard (Do, 2012) only students' artifacts are shown to teachers and it's their responsibility to interpret the data. Conversely, in the case of Lumilo (Holstein et al., 2017) or FROG (Faucon et al., 2020), students modeling techniques are used to compute the information to be shown to teachers (van Leeuwen et al., 2019). These tools mostly try to categorize students' status based on the data from their activities (Hayashi et al., 2019).

   The design challenge here is that while using learning analytic can show abstract and useful information to teachers, they might need more explanations about how these visualization are calculated (Holstein, Hong, et al., 2018). For example, if a student is labeled as *struggling* in the system, teachers might be confused as to why this label has been chosen. On the other side, the raw-level data are more easy to interpret but it might take considerable time for teachers to do so (An et al., 2020). So a balance between the interpretability of data and the time taken for their understanding is required.

To illustrate the usage of the TA framework, Table 2.2 characterizes the four orchestration tools mentioned in Section 2.5.1, w.r.t this framework.

2.6 Open Issues

The literature review in Section 2.2 shows that research in ER has developed new learning activities in robotic, programming and even new domains in STEM and has studied the impact of ER with a bigger focus on individual learning rather than teaching (Bascou and Menekse, 2016). Therefore, a still-open question in ER research is whether it would be a viable option to support learning and teaching in *classroom environments* (Alimisis, 2013). According to the literature (Mubin et al., 2013), connecting the learning activities to the learning goal is one of teachers' main concerns in robot-mediated classrooms. In this regard, two main gaps in literature were observed:

- Works focusing on finding teachers' challenges with having ER in classroom, mentioned in Section 2.2.1, mostly rely on out-of-class methodologies, like surveys/questionnaires. However, observing in-session teachers' behaviours is needed (Chevalier et al., 2016a; A. Ioannou and Makridou, 2018) to overcome the shortcomings of out-of-class methodologies, e.g. teachers' answers to the survey questions might not fully reflect what happened in the class time. Although observational authentic studies have a long tradition in TEL research (Do, 2012; Holstein, Hong, et al., 2018; Martinez Maldonado, Dimitriadis, et al., 2012), to the best of my knowledge, there is no study that *explores teachers' needs in ER class orchestration using in-session observation.*
- Works focusing on supporting teachers in ER class management, mentioned in Section 2.2.1, rarely focus on supporting teachers in real-time class management. For instance, to my knowledge, there is no work in literature that *critically observes teachers in ER classroom to understand their challenges.* Indeed, some researchers have tried to provide awareness features for teachers (Jormanainen and Sutinen, 2012) that make ER classroom management easier, however they have not focused on *evaluating their effectiveness during classroom usage.*

Stepping back to the literature on orchestration tools in TEL classrooms, discussed in Section 2.5, research has evaluated the usefulness of orchestration functionalities (An et al., 2020; Schwendimann et al., 2016). These features have been evaluated in various contexts of TEL classrooms, like multi-touch tablet-based (Granda et al., 2015; Hatch et al., 2011) or AI-enhanced classrooms (Holstein, 2019). The literature emphasizes the role of need-finding (Holstein, Hong, et al., 2018) and qualitative studies (d'Anjou et al., 2019) for designing orchestration tools. To model the teachers' orchestration in class time, I reviewed two main

Table 2.2: Characterizing the four orchestration tools mentioned in section 2.5.1 with the TA framework (An et al., 2020)

	Functionality	Target	Medium	Attention	Social Visibility	Presence over time	Interpretation
MTDashboard	Collaboration quality	What to act upon, What action to take	Tablet	Requires teachers' attention	Private	Sometimes	Less interpreted
TinkerBoard	Students' artefacts	What to notice	Beamer	Rrequires teachers' attention	Public	Always	Less interpreted
Lumilo	Students' progress status	What to act upon	Augmented-reality glasses	Requires teachers' attention	Private	Always	More interpreted
FireFlies	Teachers' proximity to students	What to act upon	Lights on students' desks	Does not require teachers' attention	Public	Always	Less interpreted

frameworks in literature: 1) Prieto et al.'s framework (Prieto et al., 2011) for characterising classroom orchestration in TEL classrooms and 2) Stein et al's framework (Stein et al., 2008), which includes practices for orchestrating productive math discussions. In summary, two main gaps in literature were observed:

- The main limitation in designing orchestration tools is their context-dependency (An et al., 2020), e.g. orchestration tools designed for university settings are not directly applicable in primary/secondary schools (Kovanovic et al., 2021). Thus, *the above-mentioned functionalities should be evaluated in new contexts, like robot-mediated classroom*. Although some of the previously-discussed contexts share some similarities with a robot-mediated classroom (e.g. the usage of technologies for learning, mostly collaborative settings, the constructivist nature of robot-mediated activities), none of them shares all the characteristics of a robot-mediated classroom (e.g. the high technical complexity and its dynamic classroom environment (A. Ioannou and Makridou, 2018)). As a consequence, to examine the validity of orchestration functionalities proposed in literature and bring new insights of how they are used in real classrooms, there is a need to evaluate their effectiveness in new contexts, like robot-mediated classrooms.

- Despite the benefits of orchestration tools in class discussions (mentioned in Section 2.4), existing research is rarely grounded in theories of orchestration of productive discussion such as the framework of Stein et al. (Stein et al., 2008): to the best of our knowledge, there is no research in the literature that studies *how orchestration tools should be designed to effectively support the key practices of OPMD*, nor whether and how using orchestration tools supports teachers in enacting OPMD practices.

Main findings of this chapter:

Robot-mediated classrooms are emerging because of the potential benefits we see in introducing ER at schools and orchestration tools for this context need to be specifically designed and studied. Our literature review highlights important gaps in literature, which lead to the following open research questions related to the orchestration of robot-mediated classrooms:

- What are teachers' needs in robot-mediated classrooms, and more specifically, in performing practices of orchestrating productive math discussions?
- What are potentially novel orchestration functionalities that can support the above-mentioned needs?
- What are the orchestration functionalities in literature that could be suitable for robot-mediated classrooms, addressing the above-identified teachers' needs?

- Is using the orchestration functionalities, specifically developed for the ER context, helpful for teachers in supporting their needs?

Throughout the next chapters, this research tries to fill the above-mentioned gaps in the literature and answer these questions.

3 Teachers’ Needs in Orchestrating Robot-mediated Classrooms

The content of this chapter has been adapted from the following works - with permission of all co-authors and publishers:

1) Shahmoradi, S., Kothiyal, A., Olsen, J. K., Bruno, B., Dillenbourg, P. (2020, September). What teachers need for orchestrating robot-mediated classrooms. In European Conference on Technology Enhanced Learning (pp. 87-101). Springer, Cham.

2) Shahmoradi, S., Olsen, J. K., Haklev, S., Johal, W., Norman, U., Nasir, J., Dillenbourg, P. (2019, September). Orchestration of robot-mediated activities in classrooms: challenges and opportunities. In European Conference on Technology Enhanced Learning (pp. 640-644). Springer, Cham.

3.1 Introduction

Before developing an orchestration tool for any context, problem identification is a necessary step to understand where the unique challenges lie (Martinez-Maldonado et al., 2015). This chapter presents the summary of the orchestration challenges faced by teachers in robot-mediated classrooms, as they emerge during class time. The observational study I conducted to this end investigates two main sub research questions related to the first research question of the thesis, mentioned in Section. 1.3.2:

- RQ1.1: What are teachers’ breakdowns in managing robot-mediated classroom resources (time, space, logistics), as defined by Prieto et al., 2011 that are caused by the robot-mediated activity?

- RQ1.2: What are teachers' actions, specific to robot-mediated activities, can be supported by specifically-designed functionalities of the orchestration tool?

The results are based on two studies. The first one is a preliminary study that explores classroom orchestration in the context of an activity with Cellulo robots in a class with 25 children, aged 11-12 years old, engaging in a computational thinking activity, explained in section 3.2. This study allows for preliminary assessing the sort of challenges that teachers might face when orchestrating learning activities involving Cellulo robots. Conversely, the main study includes observing robot-medaited classrooms using robots already in the market and consists of observing more than 15 sessions taught by 3 teachers and globally including students, aged 8-14, from 3 different schools in Switzerland. This study extends the results of the preliminary one, to the more general content of ER-enhanced learning activities.

3.2 A Preliminary Study: Cellulo robots goes to Classrooms

3.2.1 Study Context

A preliminary study was conducted in a secondary school in Switzerland with 25 students, 11-12 years old and novice users of Cellulo robots, working in pairs on a computational thinking task in an hour long session, managed by the 4 members of the researchers team. In the main learning activity, which lasted thirty minutes, the students were asked to use Cellulo robots (Özgür, Lemaignan, et al., 2017) to explore different paths on a paper map to find the optimal path, see Figure. 3.1. Prior to the main activity, students were encouraged to experience using the robots. During the activity, as the students used the Cellulo to explore a path, they received feedback from the robot through LED lights that indicated the (fictitious) battery level of the robot, which depleted as the robot is moved on a path depending on the "cost" of the path.

After the path-finding activity, the students participated in a whole class debriefing activity. For the debriefing activity, a preliminary version of a dashboard was used that displayed the number of exploration trials (a trial being defined as one instance of the robot being moved from home to target) that each team completed and the corresponding battery level at the target. During the debriefing, a member of the research team led a whole class session with the students to discuss these results and explained how the path-finding activity was tied to the concepts they were trying to learn, see Fig. 3.2. During the study, four researchers conducted the activity engaged in the classroom orchestration. After the session, the research team discussed their observations to identify common themes.

Figure 3.1: Two students engaged in the computational thinking activity with Cellulo robots. During the activity, students had to find the best path, i.e. the one with minimum cost, from a "home" to a "target" location on the map.

3.2.2 Findings

In this section, the researchers' notes and discussions around them are summarized as four points:

1) Managing robot technical failures: All the researchers insisted on the importance of monitoring the technical status of robots. In this case study, although the technical system had an overall acceptable performance, three robots failed during the activity and required intervention. In a classroom with one teacher rather than four researchers, it could take some time for the teacher to become aware of the problem, which is not efficient time management.

2) Teacher control over robot-mediated activities: Researchers mentioned their interest to control the robots for fostering the meta-cognitive skills of the students, such as changing the difficulty level of an activity or inhibiting the robots' movement to stop them from playing too much with the robot, which is one of the challenges with open-ended ER activities (Benitti, 2012). The latter could be achieved by enabling the orchestration tool to broadcast orchestration commands over robots, like pausing them.

3) Improving teachers' distributed awareness: Researchers mentioned several features of robots that can enhance teacher awareness: 1) in contrast to tablets or laptop screens, robots explicate learners' activity and collaboration patterns in groups on tables, giving the activity

Figure 3.2: The researcher shows the students' scores as a whole-class activity. Students are excited to see the results of their performance within the learning activities.

more visibility. 2) In learning tasks that require student interactions with both tablets and robots, like programming a robot, working with a robot reifies what is happening in the screen for teachers to see. In other words, instead of going to each group's desk and checking whether they finished the activity or cluttering the teacher dashboard with more information, teachers can easily understand the class performance by having a glance at all robots in the classroom, which is not possible with laptops/tablets.

4) Orchestration tools for supporting teachers in class discussion Researchers concluded that an orchestration tool can be useful in class discussions by visualizing information about the students' performance in the activity. The preliminary version of the orchestration tool, used in the class discussion activity, included bar charts comparing students' scores in two phases of the activity. Based on researchers' observations, students were engaged in observing their own behaviours and the class discussion activity helped them to understand the learning goal of the activity. For example, the researcher used students' activity data as an example to explain a point in his lecture or show the classroom performance on a central screen during an ER activity to increase competition between groups.

In this preliminary study, I explored the opportunities and challenges that ER activities bring to classroom orchestration. As a first step, researchers put themselves in the shoes of teachers to experience classroom management. From the interview with researchers, two specific challenges and one opportunity were found. These findings provide a starting point for the

Table 3.1: Summary of observation cases.

School Code	# sessions	Robotic Activity Theme	Session Time	Session Place
A	2	Robot assembly	after-school activity	workshop
B	6	Projects including building maze, programming robots	formal school time	standard classroom
C	7	Lessons on basics of robots, programming robots	formal school time	standard classroom

identification of the functionalities of the orchestration tool, which is the goal of this thesis. Prior to delving in development, it is important to verify whether the same challenges and opportunities are perceived by professional teachers, in authentic robot-mediated classrooms, and stay valid for other robots too.

3.3 An observational study: Observing teachers in Robot-mediated classrooms

3.3.1 Participants

I observed 15 robot-mediated classes, which were managed by three teachers (one male, two females, other details in Table 3.1) in three different primary schools in Switzerland. Three teachers, two experienced and one novice in the domain of robotics, participated in the study. The participants were recruited through convenience sampling, i.e. the experiment information was advertised through the network of local schools that include robotic in their curriculum and only inviting teachers who currently conducting robot-mediated activities in their classrooms. Each session had 12-18 pupils, aged 8 to 14, who were performing a learning activity with an educational robotic platform that lasted 45-65 minutes. As shown in Table. 3.1, the activities conducted by teachers during the observed sessions include robot programming, assembly and doing robot-based project. In eight sessions (cases A and B) students were performing various robotic projects (e.g., build a maze and program a robot to go through a maze), while the topic of the other seven sessions was teaching the basics of robotic and programming a robot with a visual programming language (Shin et al., 2014) (case C). In all the classes, students engaged in group activities of 2-4 students with 1-2 robots per group.

3.3.2 Procedure

To understand teachers' behaviours, I observed each teacher during their class sessions and followed up with retrospective interviews. During the class, I was sitting in the back of the classroom and took field notes. Our observations were semi-structured where it's protocol was adapted from (Holstein, McLaren, et al., 2018) and it's goal was to record all critical incidents in the classroom that were relevant to answer our research questions, introduced in Section

3.1. Every time a teacher changed an activity or a task, the observer recorded the teacher's action. When the teacher spoke with a group, the observer recorded the focus of the groups' activity (i.e., whether they were working with robots or the programming interface) and their conversations with the teacher if they could be heard. Lastly, between the changes in activity, the observer recorded periodic (every two minutes) descriptions of teachers' actions. The notes included teachers' actions during the robot-mediated activity and information about the context to make the intention of the action clearer. For instance, I recorded actions such as the teacher addressing the class as a whole (what s/he said to class), the teacher lecturing on the subject matter, whether the teacher was monitoring and teacher actions with respect to the robots, as they all could be related to our first research question about finding breakdowns in classroom management. We also recorded all teacher interventions, especially during group work, for our second research question about teacher interventions. The observer did not interrupt the learning activities, but recorded any information volunteered by the teacher during the learning activity. I did not collect any audio or video during the study.

At the end of each session (or two consecutive sessions) I conducted semi-structured retrospective interviews, in which we asked the teacher questions about the session(s) that had just concluded. Each interview lasted around 15 minutes and included questions addressing both our research questions. For instance, we asked about their experience in managing the class, via questions such as *"What was the moment that you feel stressed during the session?*, or *"What are the most important problems you had in managing this session?"*. We also asked teachers to clarify the intention behind their interventions, via questions such as *"What did you do during a specific intervention?"*,or *"Why you did visit that group?"*. To record teachers' responses, the researcher took notes as the they spoke.

3.3.3 Data Analysis

At the end of the data collection, the research team reviewed the field notes and interview notes. Some notes were split into two as the original note captured two different teacher actions. Additionally, we removed the notes describing teachers' actions that were not specific to managing robot-mediated activities, such as *"teacher is putting the chairs in their positions"* or *"checking students' attendance."*

This selection led to keeping a total of 239 notes for analysis. I used thematic analysis to analyze the data. Specifically, we used affinity diagramming to summarize qualitative patterns by iteratively clustering notes into successively higher-level themes (Holtzblatt and Beyer, 1997). First, we categorized thirty percent of the data in a joint-interpretation meeting by the whole research team. Then two researchers together categorized the remaining data. The final affinity diagram was again reviewed by the entire research team and categories were discussed and revised if needed. After validating the results, I synthesized notes to emerge categories into a 3-levels hierarchy, described in the next section.

3.3.4 Results

Table. 3.2 shows the overview of the diagram with the number of notes for each level-three, level-two and level-one theme. To visualize the recorded actions over teachers and class-time, Figure. 3.3 shows a summary of the themes aggregated over the course of all sessions, separately for each teacher. It shows with whom and when during the class each level-two theme occurred.

The three highest level themes that emerged from the data are: 1) *Management* 2) *Intervention* 3) *Monitoring*, which aligns with previous research on classroom orchestration (Prieto et al., 2011). Below, I explain each level-three theme followed by certain level-two themes, *which are unique to robot-mediated classrooms.*

1) *Management* includes all teachers' efforts for organizing the activity in class such as handling issues related to class time management, workflow, group management, robotic interfaces, etc.

2) *Intervention* refers to teachers' actions while supporting a group, which could be initiated by the group members or the teacher, or providing information to the whole class.

3) *Monitoring* consists of all teachers' actions for gathering information on the student states and that of their learning technologies, including robots and laptops. During the session, I found that teachers monitored student progress, the state of the technical systems, and assessed student activities.

Management

Teacher is managing technical system issues Although managing technical failures is a general concern for teachers in TEL classrooms (Dillenbourg and Jermann, 2010), in robot-mediated classrooms the source of the problem is unique due to the technology not being standalone and consisting of multiple parts. In the observed classrooms, the technology

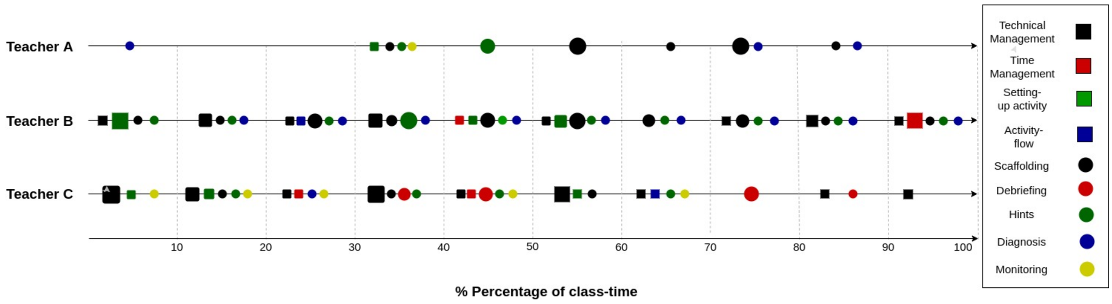


Figure 3.3: Distribution of the level-two themes, *specific to robot-mediated activities*, over teachers and their class time, which is aggregated over their sessions. The size of each icon shows the frequency of the action in that time window.

Table 3.2: The 3-levels hierarchy of the affinity diagram with number of relevant notes (the highest level is noted by bold font, the lowest level is indicated by smaller font size.)

Theme	**No. of Notes**
Management	**118**
Managing technical system issues	41
Diagnosing source of technical problem	15
Repairing	10
Replacing	7
Splitting the group because their robot is not working	4
Giving them technical hints	5
Time Management	24
Time shortage for class activity	18
Time shortage for setting up the robots before class	6
Setting up the activity	33
Distributing material among students	18
Bringing materials from storage	12
Teacher is worried about class space constraint for robotic activity	3
Teachers managing activity flow	20
Teacher wants to make sure children are wrapping up at the end of activity	13
Managing the activity keep students engaged	7
Intervention	**106**
Scaffolds such as questions and prompts	33
Asking questions to reflect on students' work	9
Elaboration questions to check students' prior knowledge and to think more about the activity	3
Encouraging students to be autonomous	6
Encouraging students to learn from their peers	5
Encouraging students to think about their strategy	10
Providing direct guidance or hints for activity continuation	25
Explaining the programming interfaces, block, menus because student didn't understand	13
Guiding student how to program and run their code on robot	12
Debriefing	16
Teacher debriefing with one group	10
Teacher debriefing in class level	6
Diagnosis	26
Strategies for diagnosing students' problems	20
Teaching students how to test their code/robot	6
Monitoring	**15**
Monitoring progress to know if they finished	15

consists of robots, personal computers and USB dongles for connecting the robots to the computers. As shown in Figure 3.3, all the observed technical failures occurred during the sessions of teachers B and C in which students were performing programming activities. Across eight sessions, teachers had to fix technical failures. Sometimes the issue was something the teacher could not address, as captured by a statement of teacher C, *"The problem is that the programming interface is not updated"* and she needed help for updating the software.

To address a technical failure, the teacher engaged in two steps: diagnosing and repairing. Due to the multiple parts involved in robot-mediated activities, diagnosing could be difficult with Teacher C stating, *"I don't know what should I change: the robot? the computer? the cable?"*

Once a issue was diagnosed, to address the problem teachers would either repair the part, replace the part, or disband the group if it could not be fixed. It was seen that teachers (case B and C) could typically solve the problem by charging a robot or reconnecting the robot. This was especially an issue if, as was the case with teacher C, they *"didn't have time to charge the robots before class."* In seven out of forty-one cases related to managing technical issues, teachers changed one part of the robotic platform (the robot, laptop/PC, or the cable) to solve the problem. This action only happened if there was enough extra equipment. As a last resort, if the issue could not be fixed, the group could be split among other groups. For example, the teacher in case C split a group with three members after failing to repair the robotic interface. Each of the students in this group joined another group of their own choice. As a result, there were groups of four and five members in the class doing the same activity that the teacher had prepared for groups of three members.

I also observed that teachers proactively tried to avoid technical failures by providing students with support on using the different pieces of hardware. For example, teachers explained to students how to use the USB dongle and reminded students to *"make sure robots are charged"* (teacher B).

Teacher is managing class time All teachers mentioned a lack of time for finishing the activity, as the teacher B said: *"I prefer to have two sessions after each other."*. Due to lack of time, the teacher A solved problems himself rather than giving hints to students and reported that, *"I usually do that [fixing students' problems] when the class runs out of time."* I observed that in at least six sessions, teachers were warning students about time shortage at the end of the class time (5-10 minutes before the finishing time) and asking students to finish the task in the remaining time.

Teacher is setting up the activity Time that is devoted to setting up the activity, like logins in TEL classrooms, is a problem for teachers (Dillenbourg and Jermann, 2010). In robot-mediated classrooms, this issue is even more critical as teachers need to take care of distributing several materials, including robots, laptops and/or other materials, such as a map or sheet for the activity, among the students. On average, 5 minutes at the beginning and 5 minutes at the end of sessions (i.e., more than 15 percent of class-time) are devoted to this activity in a robot-mediated classroom. This could be a potential cause of the time shortage discussed previously.

Teachers had two different strategies for setting up the activity: the first strategy was using a robot storage area in the classroom (cases A and B) where students could pick up their robots (in case B, students could pick any robot, while in case A each group had a specific box for their project). The second strategy was distributing the robots by teacher, as I observed in case C and asking students to help with bringing laptops.

In terms of class space for setting up the activity, an issue related to RQ1.1, two teachers were worried about the suitability of class space for setting up the activity as teacher B said, *"I want them to play on the floor. There is not enough space. I wanted them to be interactive while playing with the robot."*

Teacher is managing the activity flow Transitions between activities are one of the important aspects of classroom management (Dillenbourg et al., 2011). Whenever teachers (case B and C) noticed that a group finished their activity before the rest of the class, instead of assigning them a new activity, they tried to engage them to continue working by asking them to explore the programming interface more on their own, or as teacher in case B said, *"When they finish their activity I tell them to add extra features on what they did like adding music, clapping, or check their friends' maze."* Teachers also worked to gather students' attention, especially for debriefing. As seen with the teacher in case C, who stopped all the students activities by saying, *"Stop the robot and listen to me,"* to get the students' attention, as she described later that *"They listen to me when I ask them to stop the robots."*

In summary, in terms of management, the only teachers' challenges related to technical management that I found to be specific to ER activities relate to the spatial distribution of technology in the classroom i.e., the physical aspect of the technology and the fact that it is composed of multiple parts. Issues related to time and activity management showed teachers' dissatisfaction with managing class time and being overloaded, which is related to RQ1.1. There could be several reasons for teachers' time shortages. Specific to robot-mediated activities, becoming aware of robots failures and managing the situation is a time-consuming action. The way that awareness tools can support teachers in this issue is elaborated further in the discussion section.

Intervention

Teacher is scaffolding using questions and prompts Teachers usually provide scaffolding to help students solve problems (Kawalkar and Vijapurkar, 2013). This theme was the most common intervention that teachers engaged in and was observed in all teachers and sessions. Five lower-level themes emerged in this category: reflection (9 notes), elaboration (3 notes), encouragement for autonomy (6 notes), encouragement in peer learning (5 notes), and encouragement in strategy reflection (10 notes), which are explained below.

Reflection actions are instances in which the teacher asked students to explain their work through questions similar to *"How is your code working?"* or *"What do think happens when your robot is going there?"*. The goal of teachers was to ask students about their understanding of what their robot is supposed to do by making connections between their program and the observed robot behaviour.

Elaboration are actions in which teachers asked a question to have a better understanding of students' knowledge (e.g., *"Do you know how to use the programming interface?"*) or their work (e.g., *"Can your robot stand on its own?"*).

As the teacher in case B described, *"I want the student to go on his own when he finishes a task,"* and took actions to support students in becoming autonomous. In six notes, teachers asked students to try implementing their ideas through statements such as, *"Go and test it (your idea)."* Also, in two cases, the teacher asked students to make decisions about their activities on their own through prompts such as, *"Think about which programming language you are going to use."*

The teacher in case B believed that children *learn better from their peers*, so she encouraged groups to watch other groups' work by saying *"see what are they (another group) doing"* . Additionally, she asked a student to help another student, especially on basic matters, such as how to use the programming software.

The teachers encouraged students to think about their activity strategy. The teacher in the case B warned a student that she is putting too much time in constructing the map rather than programming the robot. In other notes, teachers asked students to change their strategies about programming, like, *"Program bit by bit,"* or about the map by asking students to be more creative, like, *"Make your map more interesting."*

Teacher is providing hints for activity continuation Teachers provided guiding hints to students to help them continue the activity in different situations. The first situation was to explain how to use the programming interfaces and robots whenever students had problems with them, as teacher C described, *"The main problem is that they don't know they should send the program to the robot."* In this case, the teachers would give hints like explaining the meaning of a block in the programming interface. The second situation was to guide the students in how to program and run their code on the robot. These hints went beyond using the robotic interfaces and were more related to the specific activity at hand, e.g. asking students to correct their programs, like *"I would recommend putting sensors in your code"*, explaining the logic of a program, or fixing a problem on their maze.

Teacher is debriefing on students' activities Debriefing is one of the well-known teachers' orchestration actions for reflecting on students' works using their own results (Do-Lenh et al., 2012). In this case, the physicality of robots nicely supported debriefing, as teachers could show the performance of a robot to the whole classroom easily. Teacher C asked questions about the performed activity by explaining the goal of the activity, by picking up the robot in front of the class and asking questions about the robot or by asking all students to gather around one group's work and discussing the robot performance while showing students the robot behaviour.

Teacher is diagnosing Compared to programming activities, robot-mediated activities pose new challenges to diagnosis. While in programming activities students can check their program line by line, in robot-mediated activities, robots behave in the continuous real world, which makes program execution line by line harder (Siegfried et al., 2017). The other challenge arises from the inherent characteristic of robots having noisy sensors and imperfect motors, thus, making the connection between the expected execution of program and the resulting robot behaviour harder to predict and diagnose (Siegfried et al., 2017).

Teachers had three main strategies to diagnose the source of students' problems. The first strategy, which appeared in two out of twenty-six cases related to diagnosis, was for teachers to help students to diagnose their problems by encouraging them to get a better understanding of what the robot should do by saying *"Put yourself in the robot's position"* or, as the teacher in case C did, by asking a group to try to *"think how their robot should behave in front of an obstacle."* In these actions, teachers were interested in supporting students to "think" about their robot behaviour, a point which will be further elaborated in the Discussion section. The second strategy, observed in nine cases, was for teachers to identify the problem in collaboration with students by observing the robot's performance and asking students to perform some actions, like *"Change the code"* or *"Press play and let's test"*. Teachers' main challenge was in having to deal with different interfaces and going back and forth between them to find a problem. The third strategy was using class resources. The teacher in case B asked students to check the performance of their robot on another group's maze or check the performance of another group's robot on their maze. This helped students find the source of problems easily. Teachers were interested in sharing class resources to diagnose students' activities and ease their workload by asking one student to teach other students (i.e., by assigning peer assistants).

In summary, teachers' interventions focused on engaging students to think about how their program is related to robot behaviour (through scaffolding) or debriefing (at class-level). Then, Other teacher interventions conversely aimed at engaging students to reflect on how they can fix their mistakes in their programs by looking at robot behaviour. Due to the importance of teachers' intervention in the classrooms and owing to the specific issues related to robot-mediated activities that I have identified, this issue is further addressed in the Discussion section.

Monitoring

All teachers mentioned their interest in going around the classroom and visiting groups one-by-one. As the teacher in case B described, *"I should check what they do . . . I wish I had eyes in back of my head."*. Two teachers went around and monitored which groups finished the task while one teacher stated that he visited groups to check if they were on-task.

3.3.5 Discussion

As seen from the themes identified above, some challenges require teachers to be supported outside of the classroom. For instance, providing a library of activities to manage the problem of activity flow management illustrated in in Section 3.3.4 or having a more informative programming interface to save teachers' time in explaining the user-interface, as mentioned in Section 3.3.4. These are not the focus of this work. Regarding the actions that can be supported by orchestration tools in the classroom, some of them are not specific to robot-mediated activities. For instance, the orchestration solutions for debriefing, monitoring students' progress and scaffolding have already been discussed in literature (Kawalkar and Vijapurkar, 2013) and can be adapted to robot-mediated activities (which is more discussed in Chapter 6 of the thesis). In line with the RQs put forth for this study and listed in Section 3.1, here I focus on those problems that are specific to orchestrating robot-mediated activities.

To answer my first research question on teachers' breakdowns in managing classrooms, I conclude that the specific problem for teachers in robot-mediated classrooms is handling the technical complexity caused by the multiple parts composing robot-mediated activities. As described in Section 3.3.4, in programming robot activities, the setup between robots and programming interfaces on students' computers involves multiple parts and steps and the setup process should be performed during class by students or teachers. This causes several problems for teachers, such as making it difficult to identify the source of technical faults, making the setup process time-consuming and requiring teachers to go around and check if the technical system is working, which is a waste of their time.

Regarding my second research question on teachers' interventions, I inferred from questions asked by teachers in scaffolding and diagnosing (mentioned in Section 3.3.4) that teachers' intentions were to make students think about the connection between their robot behaviour and their program on screen. In general, this teacher action comes back to making a connection with the underlying learning goal. In the case of this study, the idea comes back to the key skill of tracing program executions for novice programmers (Siegfried et al., 2017). This skill is even more important when diagnosing errors in robot-mediated activities, in which the challenge for students is to find the source of their mistakes across different interfaces. In this case, teachers asked students to think about how their robot is supposed to behave based on their code and what the robot actually does in the environment.

Next, I discuss how findings of teachers' needs shape the way we should design orchestration tools for robot-mediated classrooms. To address teachers' problems with handling the technical complexity of robot-mediated activities, there is a need for awareness and management functionalities about the technology (robots and their connections to programming interfaces). This functionality can assist teachers by notifying them about technical failures during class. With such a functionality, teachers do not have to go around checking if students' systems are working. Also, in terms of taking class-level decisions, knowing the total number of technical failures in the class can not only help teachers to recognize groups who have problems but also provide an aggregated picture about available technical resources in the classroom.

To support teachers in helping students make connections between their program and their robot behaviour (answer to RQ1.2), two awareness features seem to be promising. The first feature is an abstract view of the two parts of the activity (robot behaviour and program), which helps teachers to monitor the two parts of students' activities at one glance. The second feature is making the real robots behaviour in environments more clear by visualizing "what the robot sees" (through the robot sensors). This functionality helps teachers for debriefing on what students have done or explaining how their programs match robot behaviour (as seen in our data, this could for example help teacher C who was interested in debriefing). However, the added benefit of including the teacher is the pedagogical point of teachers' control over students' reflection and meta-cognitive process, which is an important factor in orchestration (Do-Lenh et al., 2012).

Limitation of the Study

Our work has limitations due to our small sample size. Some of the observed teachers' actions were only seen in a single teacher, which limits their generality. Further work is needed to replicate our results to see if the challenges are found with a diverse set of teachers and robot-mediated activities. Furthermore, this study only concerns teachers' behaviours during the class. Additional research is needed to identify teachers' needs for reflection after the class. Finally, in this study, the observer could only take field notes and we did not record the video of session due to ethical considerations. As a result, the observer could not capture all the interactions happening in the classroom.

Implications of this chapter:

The goal of this chapter was to find teachers' challenges and needs arising during ER activities that can be supported with orchestration tools. Through classroom observations in two steps (first a preliminary study and then a main study), I found that while some of the teachers' problems can be addressed by current solutions in literature, in robot-mediated classrooms two unique factors emerge that demands novelty in the design of orchestration tools to support teachers:

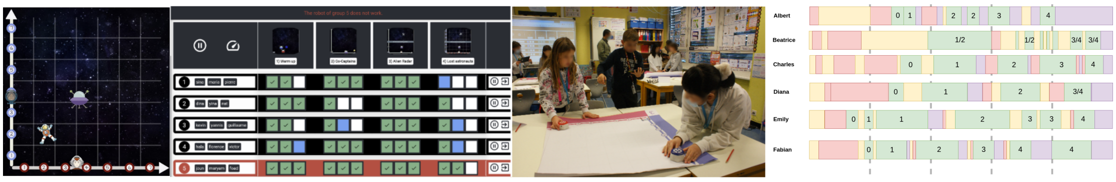
1. The robotic platform is not standalone and consists of different parts that cause technical management problem. Robots not connecting to their management software and running out of the battery are common failures in robot-mediated classrooms. Firstly teachers need to know when and where in the class these failures happen and secondly, they need technical support to handle these problems.

2. The connection between students' work in different work spaces and the learning

goal is important and challenging for teachers. Teachers expressed a wish that students engage more in reflections during the activities but it seems that one of the barriers to doing so is the lack of an aggregated view of the students' activities that could facilitate routine reflection mechanisms, like comparing students' activity.

Both of the above-mentioned teachers' needs come back to awareness of what's happening in class (on students' activity and the robots). Indeed, one of the key purposes of orchestration tools is to open teachers' eyes to what's invisible in the classroom (Dillenbourg, 2013). In the next chapters, I explore how orchestration tools should be designed to support these needs.

4 CelloRoom 1.0: Supporting Teachers in Orchestration of robot-mediated Classrooms



The content of this chapter has been adapted from the following works - with permission of all co-authors and publishers:

Shahmoradi, S., Kothiyal, A Bruno, B Dillenbourg, P. (2022). Evaluation of Teachers' Orchestration Tools Usage in Robot-mediated Classrooms. *Education and Information Technologies*, under review.

In the previous chapter, I identified teachers' main challenges in orchestrating robot-mediated classrooms, with respect to the Prieto et al.'s framework (Prieto et al., 2011). As the next step, the goal of this Chapter is to design the first version of orchestration functionalities in the orchestration tool, called CelloRoom, to support teachers in orchestrating a set of robot-mediated mathematics activities. Aligned with the second and third research questions of the thesis (mentioned in Chapter 1), specifically, I answer the following sub-Research Questions (RQs) in this Chapter:

- RQ3.1: How do teachers use the functionalities of an orchestration tool in a robot-mediated classroom? (examines the usage of the functionality)
- RQ3.2: What did teachers perceive as the effect of using the functionalities of the orchestration tool on the teaching process in the robot-mediated classroom? (examines the usefulness of the functionalities)

  Answering the above-mentioned research questions will help us understand if the orchestration functionalities have been effective in my experiments. However, as a further step, I also need to understand the teachers' purposes of using those functionalities, based on teachers' feedback and their teaching behaviours. This is important since there could be a functionality that, even though used, teachers don't find necessary to use. On the other hand, there could be a functionality which is not used due to some reason, but teachers still find useful, if modified. So we also investigate:

- RQ3.3: What was the relationship between the usage of the functionalities of the orchestration tool as identified in RQ1 and teachers' orchestration behaviours in a lesson of a robot-mediated classroom? Answering this question will help us to know whether the functionality can be a promising solution to teachers' orchestration challenges in robot-mediated classrooms in general.

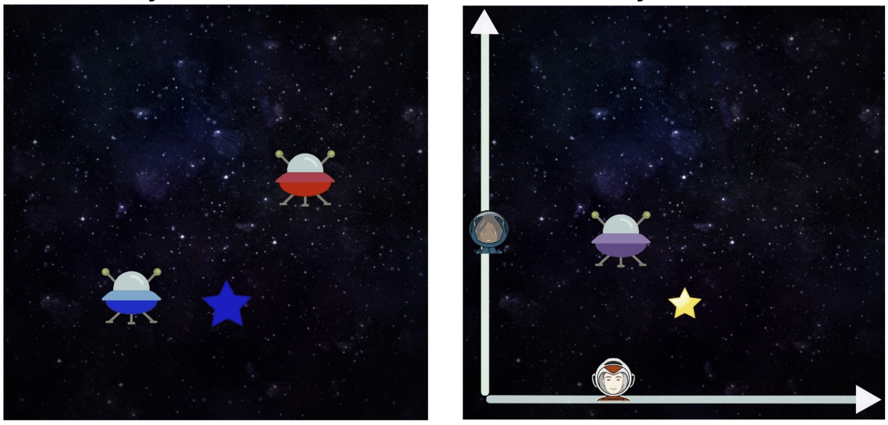
4.1 The Robot-mediated Learning Activities

The main goal of the robot-mediated learning activities is to help students, aged 7-10, learn the notion of coordinate systems. The activities are designed in a sequence such that it allows students to discover the benefits of coordinate systems as they progress along the sequence. The activities are linked by the overarching theme of space training missions for astronauts, where each mission, i.e. single activity, is played to achieve a particular training goal, for example, catching all the stars or lost astronauts, as shown in Figs. 4.1 and 4.2. The learning activities are designed as collaborative activities involving teams of three students each (as shown in Figure 4.3).

4.1.1 The Activity Setup

The learning activities are collaborative-scripted which means each team member has a predefined specific role relative to other team members to improve the collaboration (M. Rojas et al., 2022). To scaffold collaboration, in our collaboration script, each team member has complementary functionalities. The activity setup, as shown in Figure. 4.3 consists of two parts, including the physical workspace and the tablet. Students interact separately with each part and will have access to different information about the game in each part. These two parts are explained below:

1. Two students (called *Red* and Blue players) will hold one Cellulo robot (Özgür, Lemaignan, et al., 2017) each and move it on the augmented map (shown as *Cellulo red* and *blue* in Figure. 4.3) as the physical work-space of the activity.
2. The tablet app which displays the necessary information about the activity, as shown in Figure. 4.4. It shows the position of the spaceship. The guider (as shown in Figure. 4.3) will have access to additional information (like the position of the stars/astronauts to collect/save in activities 2, 3 and 4) that would enable him/her to guide the red and blue players who hold the robots.



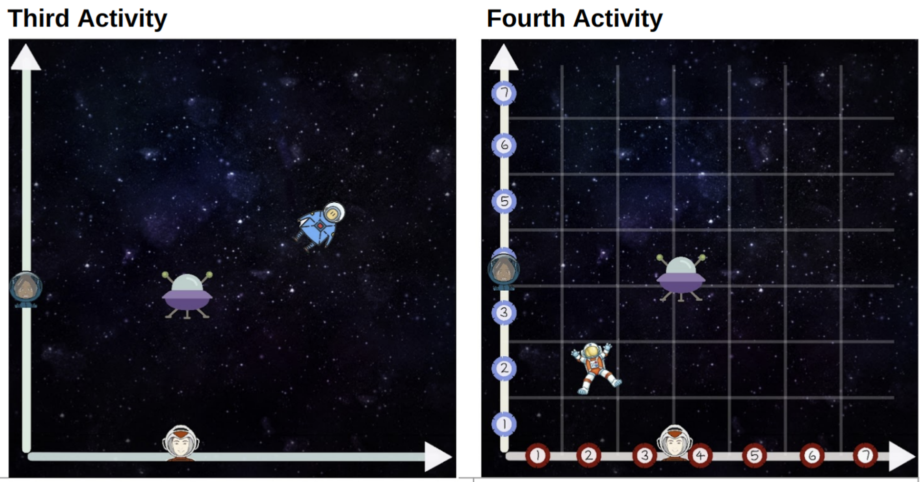
	First Activity	Second Activity
Desired Task	-Using direction adverbs to describe the position of stars and move the robots to reach them. -Understanding the game environment.	-Joint control the movement of spaceship to reach stars.
Learning Objective		-To model a point in 2D space with two independent variables. -Be able to distinguish horizontal movement from vertical one.

Figure 4.1: The first and second robot-mediated mathematical learning activities, with respective task and learning objective.

4.1.2 The Learning Sequence

The learning sequence is organized in four activities, described in detail below. Each activity is organized in three turns. At each turn, one child plays the role of the guider, while the two others play the role of *red* and *blue* players. Children change roles at each turn, so that they all practice different roles within each activity.

- In the **First Activity**, the team is in charge of guiding spaceships to catch all the stars appearing on the virtual map, without time limit (Fig. 4.1 - left). *red* and *blue* players independently drive one spaceship each, via their Cellulo robots, but they cannot see the position of stars on the physical map. The guider (who holds the tablet) is able to see the stars, but cannot move any spaceship, and should thus provide guidance to the other two. The goal of this activity is to get students familiar with the tablet app when playing the guider role and moving Cellulos when playing the *red* and *blue* players.
- In the **Second Activity**, the team has the same goal of the first activity, however there is only one spaceship which is jointly controlled by the *red* and *blue* players to catch the stars. Specifically, the red Cellulo can only move the spaceship to left or right while the other one can only move it up or down (representing the roles of variables X-Y in a coordinate system). Instead of directly introducing the concept of two-axes, we want children to construct this knowledge on their own.



	Third Activity	Fourth Activity
Desired Task	-Joint Control the movement of spaceship to reach stars in a limited time	- Using numbers to describe the target position of the spaceship in a limited time.
Learning Objective	-To model a point in 2D space with two independent variables. -Be able to distinguish horizontal movement from vertical one.	-To use numbers as coordinates to describe the object position.

Figure 4.2: The third and fourth robot-mediated mathematical learning activities, with respective task and learning objective.

- **Third Activity** follows the same structure as the second activity, but introduces time constraints. This time, children have to save astronauts lost in space, and have a limited time to reach each of them. The idea is to prepare students for the fourth and final activity, where they can see the numbers on the axes and the grid on the map, as shown in Fig. 4.2. This new feature of the game pushes students to play the game faster and discover the best strategy to play the game, since they have only a limited amount of time to save the lost astronauts.

- **Fourth** and Third activities involve the same task but with different space representation available to the students, and the rationale is to motivate students to think about what this new representation - the grid and numbers- brings to the task. This design allows to later on compare different representations (axes with vs without numbers) and thus make the advantages of using coordinate system emerge.

4.1.3 Iterative Design and Validation of the Robot-mediated Learning Activities

Before designing the orchestration tool, we needed to consider teachers' opinions in designing the robot-mediated learning activities and validate the robot-mediated learning activities with teachers. To do so, we conducted an iterative design process consisting of three phases, which are explained below and summarized in Table 4.1.

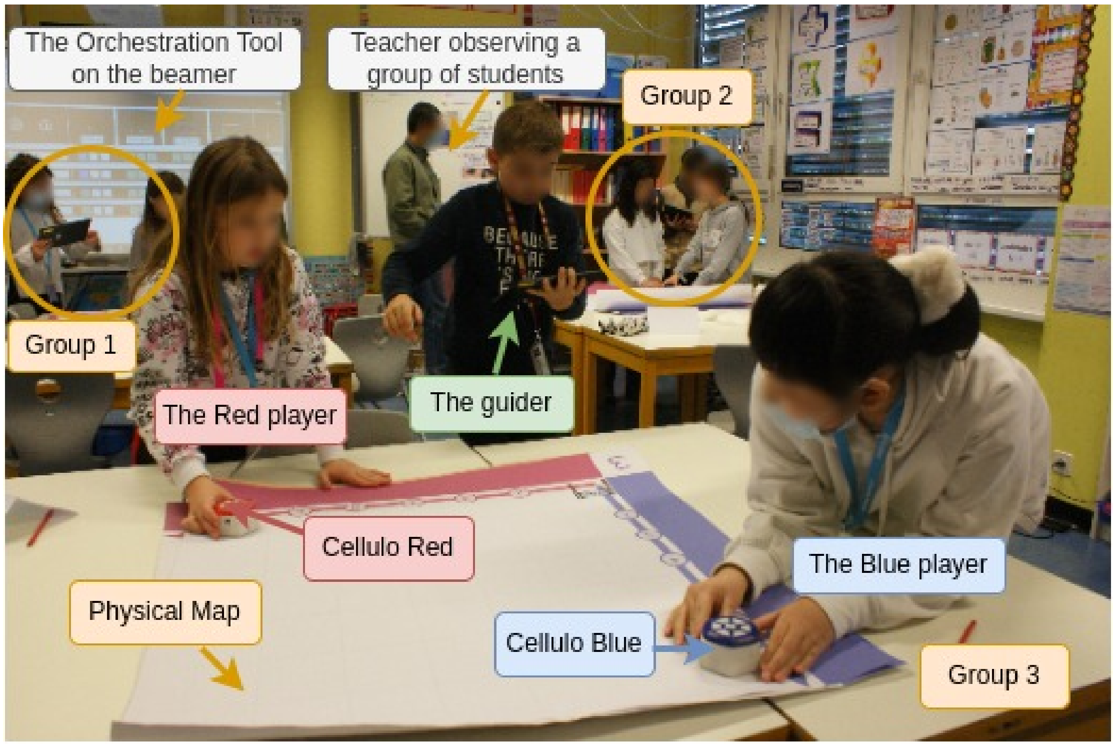


Figure 4.3: The experiment setup: students are playing in teams of three and the teacher is managing the classroom. The orchestration tool, called CelloRoom, is visible to the whole class on the beamer. The teacher is observing groups activities.

In the first iteration, four teachers played an online version of our activities with their personal computers, since due to COVID-19 pandemic the physical gathering was not an option. In this session, they provided feedback about their experience. In general, they appreciated the collaborative aspects of the activities; however they raised concerns about the technical complexity of the learning environment (as a teacher said: *It's frustrating when you have to restart the game. Quick fix technology support is needed*). Additionally, they focused on the practical issues of running these activities in their classroom, for example highlighting that the sounds in the game could create too much noise in classroom. This feedback motivated us to make the activities playable on tablets that is more suitable for classrooms. Additionally, we adjusted the sounds in the game, so that the activity sounds can be turned off in the classroom, if needed.

In the second iteration, a teacher volunteered to run the activities in his classroom to evaluate the teacher's experience in terms of classroom usability (Dillenbourg and Jermann, 2010). In this class, nine students, aged 13-15 (and thus already familiar with the concept of coordinate systems), played the activities in groups of three, while the teacher was monitoring students by going around the classroom. After the session, students mentioned the need for more description of roles in the collaborative activity and commented that the activities are better suited for younger children. Also, the teacher mentioned the importance of the game to be

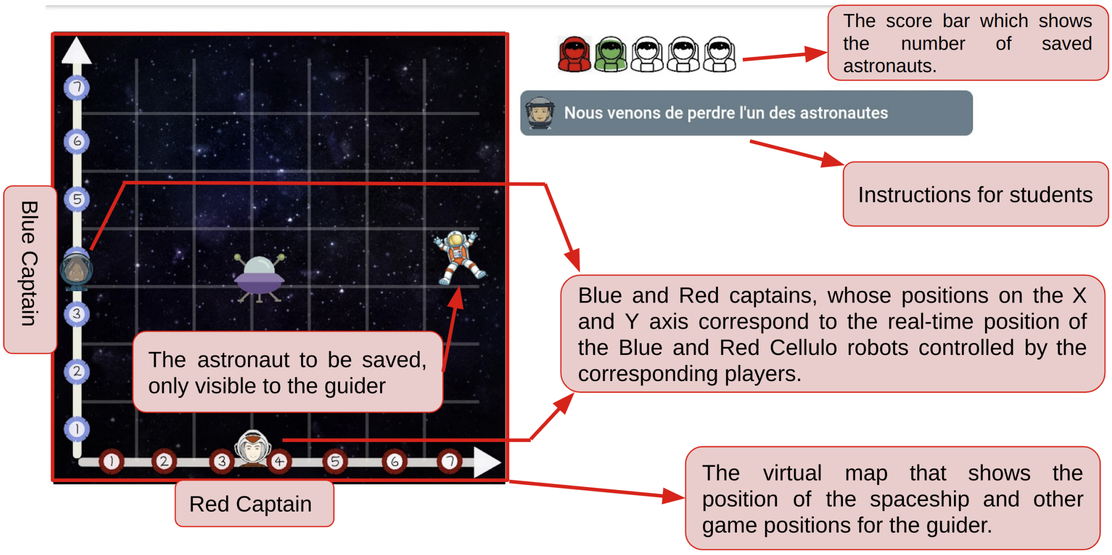


Figure 4.4: A view of the tablet app that includes the virtual map of the third activity. The app is used by the guider to guide the teammates during the robot-mediated activities.

readable and easy to follow for children, so it reduces teachers' workload to explain the game environment for students. Based on this feedback and feedback from students, we added more visuals and instructions on the screens to define the roles while playing the game, as shown in Fig. 4.4.

In the last iteration of the design process, a teacher managed an online session with our activities including three students to teach coordinates system. Although students practiced all the activities successfully, according to the teacher, the fear of losing time forced her to use direct instruction rather than letting students discover the underlying concept on their own. We realized this could be incoherent with the nature of the robot-mediated activities, aiming to promote a constructivist learning paradigm. After reviewing the literature, we realized that showing students' scores in the learning activity can be a promising way for increasing students' motivation for discussion (Do-Lenh et al., 2012) which is a necessary element of constructivist classrooms. Therefore, we tried to enhance the discussion in the classroom by adding students' game scores in the orchestration tool (Fig. 4.7) which will be further explained in the next section.

4.2 CelloRoom: An Orchestration Tool For Robot-mediated Classrooms with Cellulo Robots

The orchestration tool, called *CelloRoom*, is provided to teachers in the format of a web application. CelloRoom consists of four orchestration functionalities in two interface pages, which are shown in Figures 4.6 and 4.7. Teachers can switch between these pages from the left-side menu. Below we explain each of the orchestration functionalities and the rationale

Table 4.1: The iterative design process of the robot-mediated learning activities.

	First Iteration	Second Iteration	Third Iteration
Participants	Four teachers in a focus group.	A teacher in a mock classroom study	A teacher in an online classroom
Feedback	Practical issues of running the activities in classroom	Usability issues regarding the interface readability.	Concerns regrading the teachers' roles in the activity, such as creating discussions related to the learning goal.
Updates in the learning activity	Making the activities playable for classroom environment.	More student-friendly activity interface	Adding the product bar of students' activity score to the orchestration tool.

for including them on the basis of their established effectiveness in literature in Table 4.2. Only those functionalities are included that answer one or more of teachers' needs in robot-mediated classrooms.

4.2.1 Four CelloRoom Functionalities

- **Progress bar**: In orchestration tools, the necessary information to support teachers in monitoring the students' progress is called *progress-related* data (P. Wang et al., 2018), that are calculated based on the students' pace in the activity, for example the number of completed steps in the activity (Schwendimann et al., 2016) or more advanced indicators like students' status (Holstein, 2019) and students' progress predictors (Faucon et al., 2020). In a robot-mediated classroom, due to the diversity of students' learning strategies and teachers' limited attention, they need these data to have an overview of what is going on in the class (Shahmoradi et al., 2020). In our design, a tabular progress bar shows the number of completed steps for each group across the four activities and each turn. Each square in the table shows the group progress (Figure. 4.6). There are three possible colors that a square can take: white denotes turns that students have yet to reach, blue means in-progress and a completed turn is shown in green. The tabular design is one of the most-used visualization types (Schwendimann et al., 2016) that allows teachers to see in one glance the progress of all students. Due to its importance, progress-related data is shown on the first page of CelloRoom.

- **Robot Failure Indicator**: Shahmoradi et al (2020) mentioned the fear of robot failures as one of the most important teachers' orchestration difficulties in a robot-mediated classroom. Also one of the teachers in our iterative design emphasized this issue. To address it, we embedded a feature such that if one of the groups' robots turns off due to a technical problem, CelloRoom highlights that group with a red color on both pages to alert the teacher (for example the way group 5 is indicated in Fig. 4.6). Similar to MTDashboard (Martinez-Maldonado et al., 2014a), in which the groups at need for help are recognizable by the dashboard, this functionality can potentially help teachers to identify groups with technical problems easier and faster.

- **Management of the activity sequence (class/group level)**: According to Amarasinghe (2020), being able to control the activity sequence is one of the basic functionalities for a teacher orchestration tool. The ability to control the activity sequence at both group and class levels gives teachers different possibilities to manage the class: while some teachers might prefer that all groups progress through activities at a similar pace, others might allow advanced groups to go on their own (Dillenbourg and Jermann, 2010). In our design, students can only advance through the activities when the teacher allows it, while moving from one turn to the next within the same activity can be done by each group on their tablet. This design puts more control in the hands of teachers. It is interesting to see how teachers would use this control. Due to the importance of these functionalities, all the activity control actions are provided in the first (main) page of the CelloRoom, as shown in Fig 4.6.

- **Product bar**: As mentioned in section 4.1.3, during the iterative design process we realized the need for assisting teachers in creating discussions over the activities. Visualizing the scores of each student/group on their learning activity could help teachers' need of having information on the robot-mediated activity for reflection (Do-Lenh et al., 2012). Game-related data about students' activity is thus shown on the second page of CelloRoom (as shown in Figure. 4.7). In the first and second activities, the number of collected stars and in the third and fourth ones the number of astronauts per activity duration in minutes are shown as indicators of students' scores. In a robot-mediated classroom, this feature is foreseen to be used for two possible scenarios: 1) Increasing students' engagement by comparing groups' scores: it is possible for teachers to make a ranking to increase students' motivation by fostering competition between groups. 2) Relating students' activities to the learning goal by comparing over activities: this can be beneficial a way to link the learning activity to its learning goal, for example in the fourth activity, students use the map with grid and numbers while in the third activity, only the grid is shown (as shown in Figure. 4.2). Teachers could compare the students' scores over the activities as a way to discuss whether using a coordinate system is beneficial in these activities.

4.2.2 CelloRoom Technical Structure

CelloRoom is implemented with Flutter, an open-source UI software development kit [I], as a web application to be accessible from laptop or tablet. Figure .4.5 shows the technical

[I] https://flutter.dev/

structure of data transfer between CelloRoom and the robotic learning activities platform, consisting of a tablet and two Cellulo robots per each group. Two Cellulo robots send their positions on the map and battery status to the android application available on the tablet via Bluetooth (For more information, please refer to (Özgür, Lemaignan, et al., 2017)). Each group's application sends these data plus group's information (group name, members' names, etc) to a central cloud-based database on firestore [II] where CelloRoom has access to read from and write to. In both CelloRoom and students' application, there are software listeners that react to users' inputs; for example, when a teacher changes the activity of a group through CelloRoom, the related record to that group would be modified in the central cloud database which sequentially would fire a function in students' application to run a new function, related to the assigned activity.

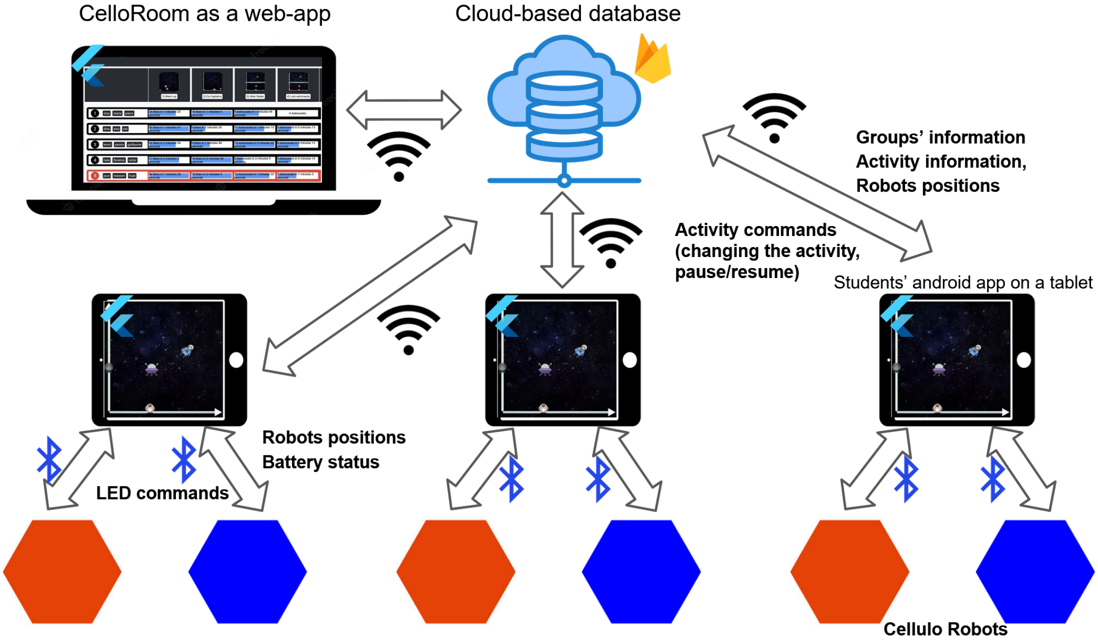


Figure 4.5: The illustration of CelloRoom technical structure in Section 4.2.2. Both CelloRoom and students' application on the tablet are implemented in Flutter. They transfer students' data, shown on the arrows, via a secure cloud-based database on Firestore. Students' tablets transfer the data including Cellulo robots positions and their battery status via Bluetooth connection.

4.3 Participants and Data Collection

4.3.1 Participants

Six primary school teachers from schools across Switzerland volunteered to run the learning activities and use CelloRoom in one class session each. The participants were recruited

[II] https://firebase.google.com/

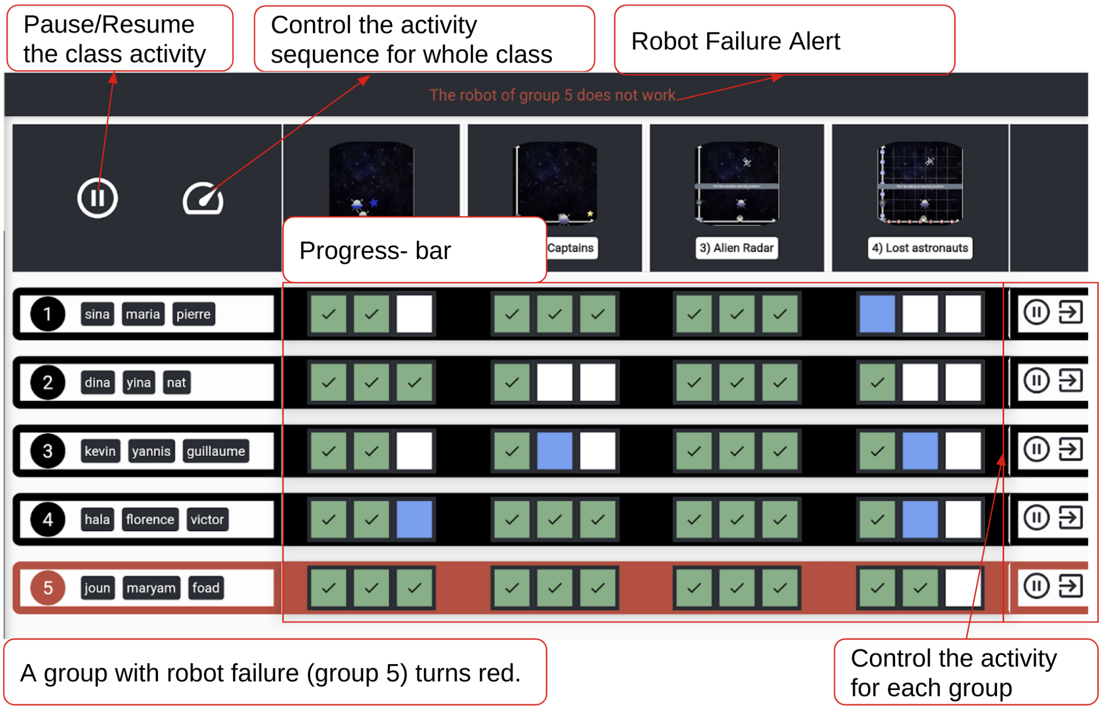


Figure 4.6: The first page of the CelloRoom interface. Each orchestration functionality is described in Section 4.2.

through convenience sampling, i.e. the experiment information was advertised through the network of local schools and later volunteer teachers contacted me to participate in the study. Each class had at least 12 students and three of them had covered a learning topic related to coordinates system in their curriculum prior to the session while the rest of classes were novice to coordinates system. All the teachers and students provided informed consent to participate in the study. Approval for the study was obtained from the Human Research Ethics Committee (HREC) at Swiss Federal Institute of Technology Lausanne (EPFL), under reference number 018-2021. According to the ethical protocol, all teachers' names were anonymized and instead fake names (Albert, Beatrice, Clara, Daniel, Emily, Fabian) are used for reference to teachers in this article. Table 4.3 summarizes the information about the participants. All teachers were accustomed to managing technologies in their classrooms, like presentations with beamers in their teaching and tablets in their learning activities; however none of them had before used any form of orchestration tool for management and robots for learning in their classroom.

4.3.2 Procedure and Data Collection

For each teacher, the researcher first presented the activities in a mock session with a duration of an hour to an hour and half. Teachers were asked to play the activities themselves, so they would get a sense of what their students would experience later on. The researcher was playing

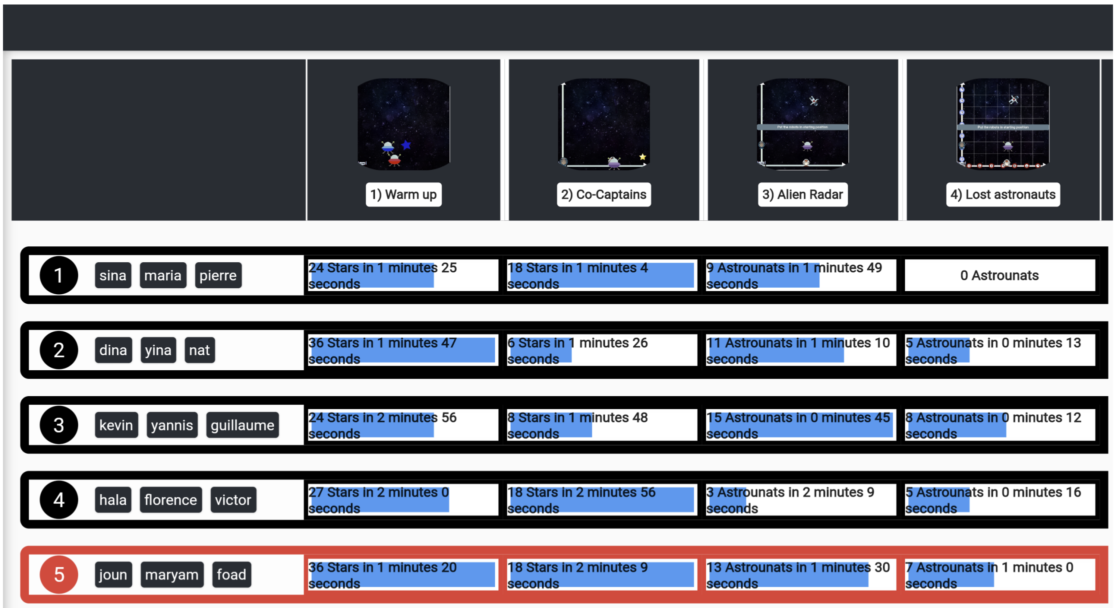


Figure 4.7: The second page of CelloRoom, that shows product bar data of students' activity scores. This orchestration functionality is described in section 4.2. (The students' name are not real.)

the role of the teacher for two purposes:

1. Teachers would get an idea of how the session could go (although they were never obliged to repeat the exact same actions the researcher did as a teacher).
2. They would see how CelloRoom could possibly be used in classrooms. After this, teachers were asked to familiarize themselves with the orchestration tool.

Before and after the robot-mediated learning activity, pre-test and post-test were performed to measure the students' learning gain to evaluate the pedagogical effectiveness of the learning activities. The pre-test contained five questions and the post-test contained six questions related to the concepts of coordinates system. Both tests were validated by teachers for clarity and coverage of concepts related to coordinates system.

The researcher was present mainly to answer possible technical questions the teacher could have about the robots (for example, when they needed to change the robots). The teacher was allowed to ask any questions from the researcher, however the researcher was not in contact with students directly and only communicated with teachers in case they had follow-up questions.

During the session, teachers wore a microphone designed for recording lectures and interviews (Røde smartlav+ [III]) to record their dialogues and interactions with students. To complement

[III] https://rode.com/en/microphones/mobile/smartlav-plus

Table 4.2: The design of CelloRoom principles.

	What does it do?	**Orchestration Aspect (Prieto et al., 2011)**	**Similar works**	**Which teachers' need addressed?**
Progress bar	Shows teachers the number of completed turns in each activity for each group	Awareness	Chao (P. Wang et al., 2018)	Teachers need an aggregated view of students' progress with the robots. Too much information to deal with (Shahmoradi et al., 2020).
Robot Failures Alert	Notifies teachers when there is a problem with one of the robots in a group	Awareness	MTFeedback (Martinez-Maldonado et al., 2014a)	Managing technical complexity of a robot-mediated classroom (Shahmoradi et al., 2020)
Activity Sequence Management	Teachers can send students to different activities at group/class level Teachers can pause/resume a group/class activity	Adaptation [of the activities sequence]	Pyramid (Amarasinghe et al., 2020), TinkerKey (Do-Lenh et al., 2012)	The need for controlling the class attention (Do-Lenh et al., 2012) To control the students' progress through the robot-mediated learning activities (Amarasinghe et al., 2020)
Product bar	Shows the students' scores (number of astronauts or stars) in each activity	Awareness	TinkerBoard (Do-Lenh et al., 2012)	Connecting the robot-mediated activities to the learning goal (Shahmoradi et al., 2019)

the audio recording, throughout the session the researcher observed their interactions with CelloRoom. Specifically, the researcher recorded these events: 1) if they look at or interact with CelloRoom on the beamer. 2) if one of the groups' robot turns off.

After the session, researchers conducted semi-structured retrospective interviews with the teacher about the session, lasting around thirty minutes. The goal of the interview was to collect teachers' perceptions about CelloRoom, as well as to know how teachers felt about the activities and the session.

To initiate the interview, teachers were asked their feeling about the recent session (e.g. *Was there any moment you feel stressed?, Did it go according to your plan for the session?*). Then, to answer the first and second research questions, the researcher asked more detailed questions

Table 4.3: The detailed information about the teachers who participated in the experiments. (Teachers' names are assigned and not real)

	Gender	*Number of students per class (age-range)*	*Years of teaching*
Albert	M	12 (8-9)	20 years
Beatrice	F	12 (8-9)	4 years
Charles	M	16 (9-10)	7 years
Diana	F	18 (9-10)	10 years
Emily	F	15 (8-9)	20 years
Fabin	M	18 (8-9)	12 years

about the usage and usefulness of each CelloRoom functionality, for example *Did you look at the progress bar in the dashboard? Was it helpful?*.

4.3.3 Data Analysis

As mentioned above, the collected data includes teachers' discourse in the session, their interviews in audio format, the students' pre-test and post-test data in the form of paper sheets and the researchers' notes in spreadsheet format. Table 5.2 summarizes the information about the data sources and how they have been used to answer our research questions. Researchers' observation notes were directly used in results. The main researcher graded pre/post test data, based on the prepared rubric.

For analysing the interviews, firstly, one member of the researcher team transcribed the interview audio files to text using Otter.ai, a speech-to-text application[IV]. Teachers' responses during the interview were segmented into 40 notes, where each note corresponds to a teacher's response to a particular question. The main researcher categorized teachers' interview question responses into one of the related orchestration functionalities, mentioned in Table 4.2 (progress bar, robot failure alert, activity sequence management and product-bar).

The class discourse was analyzed at two levels:

1. The researcher segmented the class time into the following categories:

[IV] https://otter.ai/home

Table 4.4: The source of data and the corresponding analysis to answer the research questions

	What do they represent	***Analysis Methodology***	***Related Research Question***
Class Discourse	Teachers' conversation with students	1) Speech to text 2) Categorization of notes according to the orchestration aspects mentioned in Table. 4.2 3) Making an affinity diagram in each category to extract teachers' orchestration behaviours	RQ 3
Interview	Teachers' opinions about the orchestration functionalities in CelloRoom	1) Speech to text 2) Categorization of notes into one of the orchestration functionalities in CelloRoom, mentioned in Table 4.2	RQs 2,3
Researcher's notes from in-session observation	Teachers' usage of CelloRoom	Counting the number of teachers looking at the tool on their beamer and robot failures	RQ 1

- *Logistics*: includes all teachers' efforts to setup the activity, including the group management or technical management (setting up the robots, tablets and physical maps).
- *Pre-activity, Introduction*: includes all teachers' efforts to introduce the learning activities, i.e. to explain what tasks are students supposed to do.
- *Intervention*: includes all teachers' interactions with the students while they are playing the activities, to answer questions and make sure the students play the activity as intended.
- *Discussion*: includes all teachers' efforts to engage the students in a reflection on their experience of playing the robot-mediated activity and connecting to the learning goals. The discussion normally happens in a group/class level initiated by the teacher.

2. The classroom discourse was annotated using ELAN (a professional tool to manually annotate and transcribe audio or video recordings)[V] to delve deeper into the usage and effects of the proposed orchestration tool. Firstly, the researcher segmented and categorized teachers' discourse (including the interaction with students) into one of the related orchestration aspects, mentioned in Table. 4.2 (Awareness, Activity Management

[V] https://archive.mpi.nl/tla/elan

Table 4.5: Teachers' discourse analysis: emerging orchestration aspects and related number of notes

Related orchestration aspect (Prieto et al., 2011)	Sub themes	No. of Notes	An Example Note
Awareness	- Inquiry about students' progress	15	*How many astronauts did you catch?*
	- Students and teachers exchanging information about a completed step (an activity or a turn)	20	*Did you finish already?*
	- Discussion on activity strategy	19	*Did you notice something about the person who is guiding?*
	- Students' progress	3	*This group has collected 18 stars in 7 minutes, this group collected 11 starts in 5 minutes*
	- Connection with the lesson goal	8	*So here you see a concrete example of usage of graduation for playing the game*
	- Activity follow-up	10	*Did you finish? Was it harder or easier?*
Adaptation	- Teacher informing students about the next steps	14	*Yes, I know and I'm gonna send you (in response to a student asking "we can't press the next mission [button on the tablet]".*

and Discussion). Table. 4.5 shows the number of extracted notes for each orchestration aspect. The notes in each aspect were clustered using affinity diagramming to summarize the qualitative patterns (Holtzblatt and Beyer, 1997). For each aspect, specific themes emerged from the data, like "Activity follow up" theme in discussion aspect. These themes help us to have a clearer reasoning about teachers' usage of the orchestration functionalities. For example, if they don't use the CelloRoom to create discussions, we can see whether it is because they use another approach to do so or whether they don't intend to make discussions at all.

4.4 Results

4.4.1 Sessions Overview

Before answering the main research questions of the paper, we will briefly review the timeline of six experimental sessions, which took on average 56 ± 5 minutes per session. Figure 4.8 shows the timeline for each session. In general, teachers started the session with an introduction to the goal of the session, the robots and the activity rules, including explaining the three roles that students would play in the activity. Albert and Diana, firstly, assigned the students to the groups and afterwards made sure each group had the necessary equipment for starting the activity while the rest of participants did these steps in a reverse order. For the initial technical setup, each group had to go and receive two robots and a tablet from the researcher. The maps were already placed on the groups' tables by the teachers before starting the sessions. Afterwards, teachers would explain the login process on the tablets and monitor each group in the process by going to their desks.

Teachers were guiding the students to advance through the activities. Firstly, as a warm-up activity, teachers would ask students to move their robots on the physical maps to discover the relation between the physical robots and the spaceship on the virtual maps on the tablet. This step was specifically designed to make students familiar with the activities' environment and check the technical system before starting the main activities. Afterwards, teachers made students advance through the remaining activities one by one.

In each session, some time was spent on logistics issues, such as changing the activity maps in between one activity and the next, as shown in Figure 4.8. All teachers devoted an important part of the session for discussions, as will be explained in detail in the next section.

According to the results of a paired sample t-test on the pre- and post-test data from the ninety-one students in our experiments, the normalized change (Marx and Cummings, 2007) was significantly positive (+21.5 percent, p-value = 0.0015, (+23.2 for fifty-one novice learners of the topic and +20.5 for forty learners who had had a lesson related to the topic before)).

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4.4.2 How Teachers Orchestrated the Classrooms

In this section, we analyse in detail the aspects of teachers' orchestration behaviour (Prieto et al., 2011), but only the ones in relation to the orchestration functionalities described in Table. 4.2. This section will provide a guideline for understanding the reasons behind the usage of each functionality and its usefulness.

Awareness

To become aware of students' progress, teachers mostly chose to walk around the class and directly observe each group, rather than monitoring them from afar or via the progress bar on the beamer. As reported in Table 4.5, teachers were directly asking students about their progress, via questions such as *what do you guys notice about the activity?* or *how many astronauts did you catch?*. They listened to the conversations between team-members, commented on the students' positions next to each other and intervened when necessary. Another common interaction between teachers and students was related to the completed steps in the activities. While most of the time teachers were asking students their status in the activity, sometimes students themselves would volunteer to go to teachers and report the recent progress.

Awareness for class/group discussions

Teachers were mostly conducting the discussions as a class-level activity and students were participating in the discussion. However, Albert, Diana and Fabian also encouraged group discussions. One such moment of group discussion is captured by the following conversation excerpt:

-Albert: *why did you all guys become better? why did you improve?*
-Group 2: *because we found the numbers and we had strategies*
-Albert: *you found that there is something (a strategy [which is] more efficient*).

Four types of class/group discussions, in terms of the content and teachers' purpose emerged among the sessions:

1. **Activity follow-up**: After an activity, teachers would often ask the students *"How did it (the activity) go?"* or *"Did you find the activity hard?"* to initiate a discussion. For example, Albert was asking students to compare the difficulty of activities. The following conversation is an example of one such discussion:

   -Albert: *Firstly, all of you are saying that this activity was easier?*
   -Student 1: *I think the four [activity] was the easiest because we could say go to 5 (we could use numbers), but this one (third activity) you have to just move around and you don't know (exactly).*
   -Albert: *Did all of you hear what she said? Did having numbers make it easier to play the game? How many of you agree? How many disagree?*

2. **Reflection on students' game strategies**: one topic that arose during such discussions were about the words to use when guiding the *Blue* and *Red* players, the position of the guider person to better play the game, collaboration tips, etc. For example in the following conversation, the teacher is asking students about different strategies that

students used to play the second activity in our activity sequence:

Charles: *How did you guide your friend?*
Student 1: *We used left, right, up, down.*
Teacher: *Ok! So directions! Did somebody use another word?*
Student 2: *Diagonal.*
Teacher: *Yes, diagonal! Did somebody else use diagonal? How about other strategies?*
Student 3: *Yes, other side.*
Teacher: *So we observed there are different ways to guide on space.*

3. **Showing the students' progress**: Albert and Fabian were discussing the students' game scores to show their progress and motivate them to improve their scores using CelloRoom. For example, he would ask students whether they can make their scores better and which strategies would they use to do so.

Albert: *Are you ready to see the results? Oh! Look at group number 3! You did 8 astronauts in 2 minutes. Group number two, you did 10 astronauts in 3 minutes.*
Student 1: *I think my group is [as good as] the other group, because we did more astronauts in more minutes, but they did less astronauts in less minutes.*
Albert:*Have you noticed we don't have any group just collecting 1 or 2 astronauts? Now let's compare the activities: This team did 7 astronauts, then [they] did 3 astronauts in 5 minutes, 4 astronauts in 2 minutes. Do yo think they improved a lot? Did you all improve?*
Class: *Yes!!*

4. **Connection with the learning goal**: Albert, Charles, Diana and Fabian were asking, after the activities, if anyone could remember a mathematics topic that relates to the activities, for example:

Fabian: *Okay, some great skills in your group communication. What about the math skills? The robots may have taught us something?*
Student 1: *Placement.*
Student 2: *Position.*
Fabian: *Placement? position? Two very important words. Position matters. Definitely. And also in awareness of starting in the right position.*
Student 2: *[Where to] Start. Position. Being accurate.*
Fabian: *Excellent. So today, you've actually been learning all about something called coordinates. So knowing the coordinates, it make finding the position much easier for you. right?*
Class: *Yes!*
Fabian: *So the goal of this lesson was to help you understand what coordinates are. [It's] much easier saying the coordinates, rather than saying "a teeny weeny bit to the right". I love them but do you think using the coordinates was easier?*

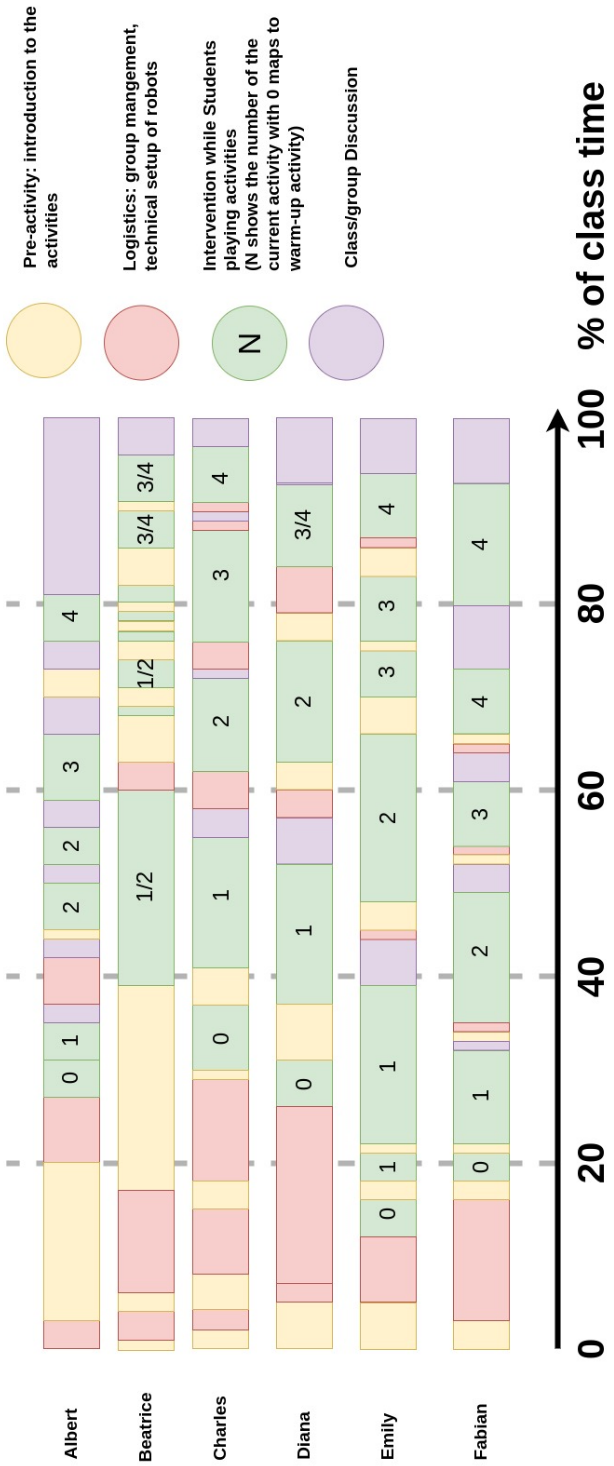


Figure 4.8: The comparison of timelines of teachers' actions in their sessions highlights similarities and differences between their activity management patterns.

Table 4.6: Teachers' Usage of the Robot Failure Alert

	Number of robots	***Number of failures***	***Noticed by the Alert***	***Validated from the Alert***	***Did not use the Alert***
Session 1	8	0	0	0	0
Session 2	8	1	0	1	0
Session 3	10	2	0	0	2
Session 4	12	1	1	0	0
Session 5	10	1	1	0	0
Session 6	12	1	1	0	0

Adaptation

In general, teachers did not skip any activity, although Albert decided to make the first activity shorter to have more time for the other activities (see Fig 4.8). Charles and Fabian repeated one or two activity because of different reasons: Charles repeated the activity whenever a group had to wait for other groups to finish. Fabian repeated the fourth activity, so students have an opportunity to practice their skills in the activity.

Two patterns of activity sequence management were observed:

1. Albert, Charles, Diana, Emily and Fabian had a synchronous class-level management where the whole class was advancing through the activities at the same time and teachers were verbally or through the orchestration tool asking students to stop the activity to initiate discussions in between one activity and the next. These teachers found it easier to manage all the teams together, as Charles says: *When every student is not on the same level, (this group is [doing an activity] and the other group is [doing another activity]. [I] have to always adapt myself with. I think it's the best if every group [would be] in the same activity*. While in most cases, students were almost paying attention to the teacher when they were asked to stop/start the activities, in Emily and Fabian's classes, they had difficulty capturing students' attention, as children were continuing their interaction with the robots or the tablet, when not supposed to.

2. Conversely, Beatrice preferred to manage the class asynchronously, letting some groups be more advanced than others. As a result, there were no class discussion moments between the activities (See Fig. 4.8). In both patterns (synchronous or asynchronous), when a group has finished their activities, they would ask the teacher about the next steps. However, in the second pattern (asynchronous management), the teacher would explain the next step and advance the particular group.

4.4.3 Teachers' Usage of the functionalities in the Orchestration Tool and its Usefulness

All teachers had the CelloRoom on the beamer connected to their personal computers, as shown in Fig. 4.3. Only Fabian used the tool also on the tablet. Below, we describe in detail the usage of each orchestration functionality, its effects on teachers' behaviour in the classroom and the reasoning behind teachers' behaviour, based on their post-session interviews.

The progress bar

According to the researchers' observations, four teachers looked at the progress bar as follows: Beatrice (4 times on the beamer), Diana (2 times on the beamer), Emily (6 times on the beamer) and Fabian (he looked at the tool multiple times on his tablet). On the importance of the progress bar, in the interviews, Emily said:

> *It[progress bar] was useful because it helped me to keep track of [students' progress], Should I wait for everybody to finish [their activity]? Because most of the time I had one group that was late and it[progress bar] helped me to know [which group is it], because sometimes when you're teaching, this [finding students' progress] is taking a really long time.*

On the other hand, the other teachers (Albert, Charles and Diana) did not mention any interest in the progress bar in the interviews. Two possible reasons for this behaviour have emerged from the interviews:

1. Teachers felt that by only looking at CelloRoom, they will miss important aspects of students' learning progress, as Albert said: *I prefer to visit the groups. I can see what they are doing. If I only use the [CelloRoom], I miss the conversation. I miss the body language.*
2. They don't feel the progress bar would inform them of something that they could not understand by visiting groups. For example, to decide about students' transition to next activity, Charles preferred to listen to students, as he says *They [students] were actually telling me [that] it's finished. I said, so the majority is done. So, we can now go on to the next stage.*

   These reasons align with teachers' preference of moving around the class and directly monitoring the groups one by one rather than remotely monitoring them all via CelloRoom, as mentioned in Section 4.4.2.

Robot Failure Alert

In total, there were six cases in which one of the groups' robots had a problem that needed teachers' intervention. Table 4.6 shows the distribution of the failures among the sessions. *Noticed by the Alert* column shows the number of times in which teachers noticed the failure by looking at the CelloRoom while *Validated from the Alert* column is referred to the failures in which teachers only look at the CelloRoom after noticing the failure by students to validate their claim. The rest of times teachers were noticed by students about the failure Mostly teachers were alerted by the CelloRoom about the robot failure. For example, in one of these cases, Diana looked at CelloRoom and then she said *where is group 3, there is a problem with your robot*. Then, she asked the researcher to replace the robot with the technical problem. Fabian and Emily had the same reaction when they noticed the failure alert. In other two cases, teachers only noticed about the robot failures after the students raised the issue. Another interesting usage of the failure alert was observed when Beatrice looked at CelloRoom to validate students' claim that their robot was not working.

From teachers' behaviours and interviews, it seems that a combination of the orchestration tool and students' direct feedback were the sources for teachers to get aware of technical problems. Both approaches find support in the teachers' interviews:

- Beatrice said *When one of the robots turned off, the whole group [bar on the tool] became red. And it was very clear, for me to know that something is wrong*.
- On the other hand, Diana mentioned that the information about robot failures came from students and there is no need for CelloRoom to alert that: *they (students) say it right away. They would tell me [that] this (the robot) is not working. So please fix it.*

Activity Sequence Management

Teachers used this feature every time they needed to move the students between activities (to move the entire class or just a group) (as described in Section 4.4.2). Having the ability to control the sequence of each group individually empowered teachers to run the class both in synchronous or asynchronous manner, as Beatrice said: *I like the fact that I can send students to different activities individually*. Teachers preferred to have the control over students moving between the activities mainly because each activity requires an introduction, however they still like to have the option that at least some groups move on autonomously, as Albert said: *That would depend on the group dynamics. For these two groups, I don't want to have control, so they can go on their own. With that group, I want more discussion and coming back to group number 2 and asking them why there are successful?* The other theme that emerged from teachers' interviews was that teachers preferred to be able to control the activity sequence themselves, as Charles says: *I think the dashboard is very important, because without the explanations they would be asking too many questions. What do we need to do? And I think it would be horrible to deal with that.*

Two teachers (Emily and Fabian) used the pause/resume buttons on CelloRoom. They found this functionality helpful to get students' attention when they are distracted by the robots as Fabian said: *If I had to get all their attention to have a little discussion between activities it could be difficult, because children at this age easily get distracted. So with the pause button, it* *was really useful that I got their attention.* Other teachers grasped students attention by calling out to them verbally. Although in some cases teachers had to call students few times to get their attention, they did not report having a major difficulty in doing so.

Product bar

Albert and Fabian used the product bar on the beamer at the end of the fourth activity. They showed students their scores in the activities to show their progress, for example Albert said: *Now let's compare the activities. This team did 7 astronauts then did 3 astronauts in 5 minutes, 4 astronauts in 2 minutes. Do you think they improved a lot? Did you all improve?*

Students were excited to participate in discussions and were trying to provide reasons for their success/failures as a student said: *I think my group is same (as the other group) because we did more astronauts in more minutes but they did less astronauts in less minutes.* In case of Albert, using the product bar led to students' engagement and creation of a summarize-discussion moment in the classroom, while for Fabian only it was used to motivate students to improve their scores by repeating the fourth activity.

Even though only Albert and Fabian used the product bar in their teaching, all teachers mentioned their interests to use the product bar and said that if they were to do the same session again they would use the product bar. Emily and Fabian doubted using the product bar *while* students were playing the activities as it might get them into unhealthy competition, as Emily said: *I didn't use the [product bar], since it might make kids more competitive. I was worried that it would get them very frustrated. They would end up in some arguments instead of having a healthy competition. I was afraid that [children think] is my group doing better [than others?] and would end up in frustration.*

4.5 Discussion

This study aimed at evaluating the usage and usefulness of the four orchestration functionalities I designed based on the assessment of teachers' needs in the context of a robot-mediated classroom (second and third research questions of the thesis, mentioned in Chapter 1) and understand the relationship between the functionalities and teachers' orchestration behaviours. These results are summarized in Table. 4.7. In this section, I discuss whether each of these functionalities can be promising for the context of robot-mediated classrooms and, if promising, reflect on how it should be implemented.

4.5.1 The progress bar

The progress bar functionality was on the main page of CelloRoom (Figure. 4.6) and teachers could easily interpret it, according to their feedback. In terms of its usefulness, opposing ideas emerged in the interviews:

- Three teachers believed the progress bar helped them to decide the moment to stop the activity and have a class discussion or make some groups repeat the activity. One teacher used the tablet to monitor the progress bar, while others found the beamer the best option for using it in class. These results are supported by the literature finding students' completed steps as an important indicator in orchestration tools (Faucon et al., 2020; Haklev et al., 2017; Schwendimann et al., 2016).
- The other three teachers did not favor using it in real class-time. According to their in-session behaviours and interviews, the reasons could stem from two important characteristics of our experiment context:
  - **The educational level:** An alternate awareness source for teachers in our experiment was teacher-student communication to know the number of completed steps, directly from students, as mentioned in section 4.4.2. Especially in primary schools in which the teacher-student relationship is closer and there are fewer students per class than in typical university settings, teachers are more independent in monitoring their students.
  - **The learning technology:** robot-mediated activities (and in general table-top activities) provide an easy-to-monitor setting for teachers, unlike screen-based activities (Shahmoradi et al., 2019); thus paying attention and monitoring students' desks becomes even more important. According to their statements in the interviews, teachers consider checking/using another medium (such as a tablet or computer), a sort of a barrier rather than an assistant, as Diana said: *I don't like it when every time I have to go and click on my PC [to interact with the dashboard].* Similar results have been obtained from teachers' interviews in literature (Amarasinghe et al., 2020; Holstein et al., 2019). As an alternative, distributed orchestration tools (Alavi et al., 2009) could provide the same progress information in CelloRoom, however teachers' focus would be integrated into the class routine (on students' desks).

4.5.2 Robot Failure Alert

From the results, we can say that teachers viewed robot failure alert functionality as a reliable source for getting informed about technical failures. Since the alert was highlighting the group in need and it was shown on the main page of CelloRoom, they could easily see it. In all cases, teachers changed their order of visiting groups to quickly reach the groups with a problem. Similar orchestration behaviours of prioritizing helping groups in need, according to the data from orchestration tools, have been reported in literature for detecting collaboration deficiencies (Martinez-Maldonado et al., 2014a) or students' misuse of the learning system (Holstein et al., 2019). What makes the robot failure alert different from the alerts mentioned in literature, is the fact that students were also the source of alert awareness for teachers, which is not the case with students' misuse of learning systems. According to some teachers in the study, relying on students itself, could replace the orchestration tool, but even in that scenario, the data provided by the tool can still act as a validation. As a next step, the orchestration tool should provide more information on the action that the teacher should take (for example, to change the robot).

A burden to use the tool for being aware of technical failures (or in general urgent events) comes back to the point that teachers don't look at the tool while going around the class, as mentioned earlier in section 4.5.1. Wearable tools, like smart watches, could solve this issue by notifying teachers about urgent events without requiring their attention all the time (Quintana et al., 2016).

4.5.3 Activity Sequence Management

It is no surprise that teachers used the orchestration tool to move the students between activities as that was the only way to do so. However, it is interesting to evaluate its effect on the teachers' orchestration behaviour. Most teachers ran the class synchronously (they moved all the groups between activities together) and supported the idea of controlling the students' progression along the sequence of activities (by starting and ending the activities). The same results have also been reported in the context of an university class (Amarasinghe et al., 2020). However I believe in the context of primary schools, teachers are more interested to control the activity sequence, due to teachers' greater command over students' actions, compared to a university class. An example in this study is when students would come and ask a teacher if they can go to the next turn (which they could do even without asking the teacher) as Beatrice said, *I would normally prefer for them to go on their own. But I saw it as a theatrical opportunity, you know, like for them to have some kind of a closure, like a full stop at the end of the sentence. So I go and they press the button, but its not at all necessary!* As we observed in our study and as also seen in similar works in literature (Olsen et al., 2018), teachers don't like to have the activity sequence control *all the time* and in some cases they prefer to keep the students autonomous. Thus, they appreciate being able to send individual groups to specific activities or making students advance autonomously.

In our study, the activity sequence was pre-determined, however to generalize this functionality in various robot-mediated classrooms, it requires a pre-scripted learning sequence for each class. Therefore, further study is needed to design orchestration tools for robot-mediated activities that makes the teacher able to design their own robot-mediated lesson script before running the session, similar to the FROG orchestration tool (Haklev et al., 2017).

According to the literature (Amarasinghe et al., 2020) and also our teachers' in-session behaviour, the ability to keep students' attention (by pausing the activities) was important for teachers to create discussions or giving important messages to students. While some teaches could keep the attention of the class without difficulty, using their traditional methods to do so (mostly verbally), two others found the pause button helpful in getting students' attention. These findings suggest that as long as teachers can efficiently perform an orchestration action they don't need to use digital tools, which makes sense since orchestration tools are supposed to augment teachers' orchestration, not to replace them (An et al., 2020).

According to interviews, a missing action in CelloRoom was the possibility to repeat the activity which was mentioned by two of our teachers (Charles and Fabian). This functionality was important for them to keep the groups who finish the activity faster involved until the rest of the class is ready for the next activity or to make students practice their skills.

4.5.4 product bar

Although both the product bar and the progress bar are supposed to support the teachers' awareness of the class progress, each provides information at a different level: while the product bar data empowers teachers to create engaging discussions *after* the activities, the progress bar is mostly useful for monitoring *during* the activities.

Despite all teachers' interest in showing the solutions to their students, some teachers (four out of six participants) did not use it. This gap between teachers' opinion about the functionality and their real usage could be because of two reasons:

- Lack of enough time was the main reason for those teachers who did not use the product bar. However we should consider that all teachers used CelloRoom for the first time. As mentioned by one of our teachers, they were overwhelmed by running a new set of activities and using a new tool which could be a reason that they felt short of time.
- Teachers' fear of creating unhealthy competition among students was mentioned by two participants. For teachers, creating engagement is necessary to continue the class activities (Bergdahl and Bond, 2022), however excessive engagement from students can make the class out of their control which hinders the learning process. As a result, public orchestration tools, like the product bar, in the context of primary schools are only suitable if its information does not create an undesired chaos in class. Similar results were observed by using *FireFlies*, a distributed orchestration tool, in which students only found it useful if there is no stigmatizing effects (they don't feel they are labeled) (d'Anjou et al., 2019).

Among the four discussions themes that teachers created in the classroom, in our study the product bar was only used for showing students' progress and making them engaged with the activities. We argue that the usefulness of the product bar could be extended to other discussion themes. Similar usage of showing students' products for supporting reflection in the class has been successful for creating connection with the learning goal in constructivist activities (Do-Lenh et al., 2012), and it can similarly happen in robot-mediated activities. However for every activity these measures that help teachers create a reflective discussion about the learning goal should be carefully designed, based on the students' interaction with the robots and the learning goal. For example, in a robot programming activity the measure should be based on the students' program and the corresponding robot behaviour (Shahmoradi et al., 2020).

Implications of this chapter:

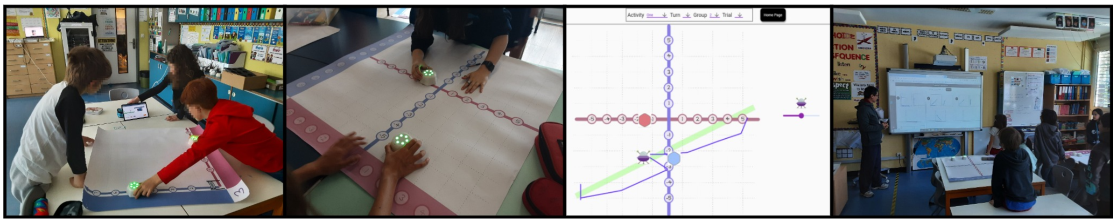
This chapter presents the results of the first classroom evaluation of orchestration tools in the context of robot-mediated classrooms. The orchestration tool, called CelloRoom, gave teachers flexibility in controlling the activities sequence synchronously (class-level) or asynchronously (group-level) and provided different levels of awareness indicators that helped teachers in making activity-transition decisions and summarize-discussion moments. Moreover, it served as a reliable source for detecting hardware problems with the educational robots.

While, in general, in all classes positive learning gains were observed and teachers had a general positive opinion about the way robot-mediated activities worked in their classes, the results showed different teachers' usage and opinions about the same functionalities in our proposed orchestration tool: An orchestration functionality (named progress bar) that is used by some teachers was not favored by the others; Same orchestration functionality (activity sequence management) was used differently among teachers. This is an example of the complexity of generalizing orchestration functionaries over teachers, as also has been discussed in the literature (Schwendimann et al., 2016). This result shows that besides learning context, also *class dynamics* plays an important role in usage of orchestration tools, for example students' scores in their robot-mediated activity was used in one class while in the other one teacher did not use it to avoid unhealthy competition among students.

Table 4.7: Evaluation of the orchestration functionalities: Each column answers one of our research questions.

	Usage (Answer to RQ1)	***Usefulness (Answer to RQ2)***	***Usage-behaviour relationship (Answer to RQ3)***
Progress bar	Three teachers looked at it on the beamer (Emily 6, Beatrice 4 and Diana 2 times). Fabian used it on his tablet when he was going around the class.	While three teachers found it useful to decide the moment to transit between activities, the others did not found it useful.	Teachers who did not use it relied on teacher-student-communication for awareness. Sometimes, students would go to teachers when an important step had been accomplished.
Robot Failure Alert	Diana and Fabian prioritized their group visits based on the alert. Beatrice validated the possibility of a robot failure raised by a group by looking at the alert.	Faster and more reliable awareness of a robot failure.	Teachers were using both teacher-student communication and the orchestration tool as sources to get aware of technical failures.
Activity Sequence Management	All teachers used it to advance students in the activity sequence both at class and group level.	Flexibility in choosing the approach for controlling the activity sequence (synchronously or asynchronously)	The tool allowed teachers to have control of students moving between the activities mainly because each activity requires an introduction, however they still appreciate having the option to let at least some groups move on autonomously.
Product bar	Albert used it to create a summarize-discussion moment. Fabian used it to motivate students to improve their performance.	Teachers found the information useful to motivate students but only *after* playing the activities. They conditioned its usefulness on not creating unhealthy competition among students.	The product bar was used for one discussion theme while three other ones also were observed.

5 CelloRoom 2.0: Supporting Teachers in the Orchestration of Productive Math Discussion



The content of this chapter has been adapted from the following works - with permission of all co-authors and publishers:

1) Shahmoradi, S., Kothiyal, A., Bruno, B., Dillenbourg, P. (2022, October). Empowering Teachers In Orchestrating Class Discussions: The Role Of Learning Dashboards In Orchestration Of Productive Math Discussions. Submitted to the 2023 CHI Conference on Human Factors in Computing Systems, under review.

Building upon the positive outcomes of the CelloRoom 1.0, in this chapter, I discuss the case of bringing a new set of activities together with the updated orchestration tool, CelloRoom 2.0, to classrooms. In this chapter, my aim is to study the usage, usability and usefulness of CelloRoom 2.0, specifically for Orchestrating Productive Math Discussion (OPMD). As mentioned in Chapter 2, class discussions are an essential part of robot-mediated activities which should be orchestrated by teachers. This chapter evaluates the usefulness of CelloRoom 2.0 with the goal of discussing the potential of orchestration tools in orchestrating productive math discussions. This chapter also provides design guidelines for orchestration tools in robot-mediated classrooms, based on the results of the user studies reported in Chapters 4 and 5. Concretely, related to the second and third RQs of the thesis, this study aims to investigate the following sub research questions:

RQs3.1 and 3.2: How did teachers use the functionalities of CelloRoom 2.0 including robot failure alert, activity management and product bar during class time and what was their opinions its usability and usefulness?

RQ3.4: Does the usage of the product bar support teachers in performing the three practices of OPMD, namely selecting, sequencing and connecting, mentioned by Stein et al.'s framework (Stein et al., 2008)?

5.1 Robot-mediated Learning Activities

5.1.1 Learning Objective

Broadly speaking, the learning activities used in this work were designed to help students, in the age range of 9-14, learn the concepts of *line slope* and *intercept.* Specifically, the aim is for students to learn:

- That the slope or gradient of a line is a number that describes both the direction and the steepness of the line (Tuluk, 2020).
- That the intercept of a line is a number that a point on the y-axis, through which the slope of the line passes (Tuluk, 2020).
- How to describe a line with the aid of line slope and line intercept.
- How to draw a line knowing its slope and intercept.

Following the learning goals, four specific learning tasks can be derived:

- Robots should move at a same time.
- The relative speed of robots should be proportional to the slope of the line.
- Robots should move, orthogonal to each other, along the Cartesian axes.
- A learner in the team with the role of *Guider* should recognize the roles of robots in X and Y directions correctly.

The activities are a sequence of four activities in the format of challenges for students, with the goal of gradually exposing students, working in groups of three, to use the line slope and intercept to model a line. In each activity, the group is in charge of guiding spaceships to follow the line appearing on a virtual map on the group's tablet, with the difficulty increasing from one activity to the next. I used the two parameters of the social level of the activity (individual then group activity) and the time-limit to increase the difficulty level of the activities.

5.1.2 The Activity Setup

The learning activities are adapted from the one in Chapter 4 (for more information, please look at Section 4.1.1). The activity setup, as shown in Figures. 5.1 and 5.2), consists of two parts, including the physical workspace and the tablet, whose functionalities are explained below.

1. Two Cellulo robots (called *Red* and *Blue*) which are held by one or two student(s) (depending on the level of the activity), to be moved on the physical map to follow a target line. In the activities, specifically, the Red Cellulo can only move the spaceship to left or right while the Blue Cellulo can only move it up or down (representing the roles of variables X-Y in a coordinate system).
2. The tablet app displays the necessary information about the activity, as shown in Figure. 5.1, left. It shows the position of the virtual spaceship which is updated in accordance with the movement of the Cellulo robots on the physical map. The app also shows additional information with respect to the physical map, and specifically the target line that students have to follow. The movement of the robots draws a path for the spaceship on the tablet, which is considered as the *group's solution* in the activity. To help students who move Blue and Red Cellulo robots when following the target line, the LEDs on top of Cellulo robots illustrate the degree of closeness to the target line at each point with different colors, following a coding for colors in which green shows that the group's spaceship is exactly on the line, orange that it's near the line and red shows that it's far from the line.

The above-mentioned activity setup is envisioned to help students illustrate the abstract concept of line slope as a tangible visual concept on the physical map. For following lines with different slopes, the movement of the Cellulo robots (and their relative speed) have to be adapted (for example for following a line with higher slope the Blue Cellulo should go faster relatively to the Red Cellulo). In particular, learners are expected to understand that the slope of the line is determined by the relative speed between the two Cellulo robots, i.e., if the slope equals to 1, when the red robot is moving by 1 unit in the positive direction, the blue robot should also move by 1 unit in positive direction.

5.1.3 The Learning Sequence

- As a **Warm-up activity**, each student, as shown in Figure. 5.1, would take two Cellulo robots in his/her hands and try to follow the line shown on the tablet. Each student would try to draw three lines in each turn. This activity is designed to give students practice in using the activity environment. They should understand how the movement of the robots on the map relates to the spaceship movement on the tablet. This activity also gives them a very first idea that for following lines with different slopes, the movement

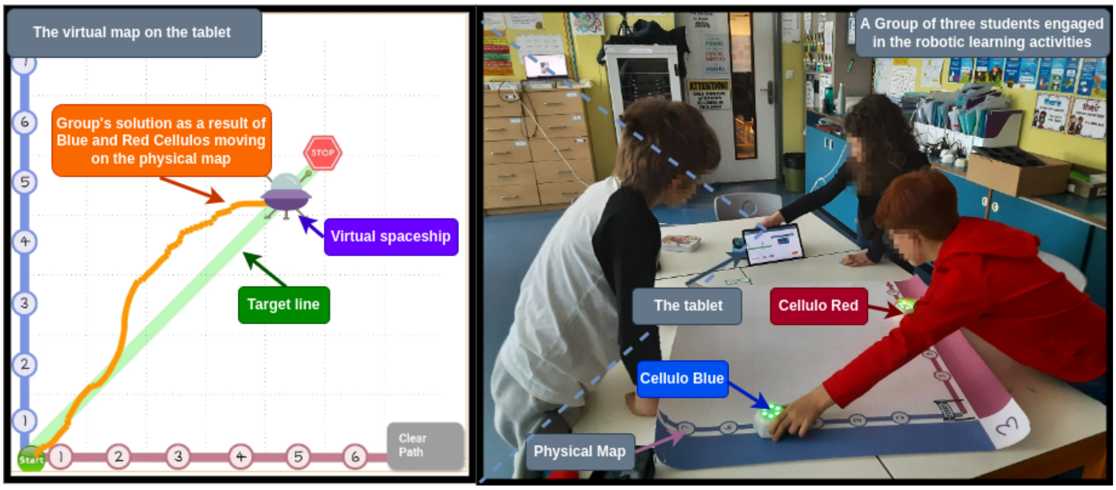


Figure 5.1: **Left**: A view of the tablet app that includes the virtual map of the first activity, as an example. The app is used by the students to have activity information, mainly the target line and the group solution, during the robot-mediated activities. **Right**: Students are playing the warm-up activity in teams of three. In this activity, the student with the red shirt is moving both Cellulo robots to follow the line shown on the tablet. The student with the black shirt is helping the other student by holding the tablet.

of Cellulo robots (and their relative speed) needs to be adapted accordingly. Students feel the relative movement of the robots with their hands.

- From the **first activity** onwards, all the activities are collaborative such that each team is in charge of guiding spaceships to follow the line on the tablet appearing on the virtual map (Figure. 5.2). Red and Blue players independently drive one spaceship each, via their Cellulo robots, but they cannot see the target line that hey have to follow. The guider player (who holds the tablet) is able to see the line, but cannot move any robots, and is thus in charge of providing guidance to the other two persons in the group.

- In the **second and third activities**, the group has the same objective as the first activity, however the group has decreasingly limited time (60 and then 45 seconds) to follow the lines.

5.2 CelloRoom 2.0

5.2.1 From CelloRoom 1.0 to 2.0

According to the results of the implementation of CelloRoom 1.0 (mentioned in Chapter 4), I designed and developed an updated version of the orchestration tool, called CelloRoom 2.0. Figures. 5.3, 5.4, 5.5, 5.6 and 5.7 show the updated version of the dashboard. I explain these updates in below:

Figure 5.2: Students are playing the first activity, which is similar to the warm-up one, shown in Figure. 5.1, however in a group-level. In this activity, instead of one person holding both robots, two students hold one robot each moving them along the X and Y axes (corresponding to the red and blue sidebars on the physical map). The person who holds the tablet is the guider and has to guide the two others to follow the target line shown on the tablet (Figure. 5.1, left).

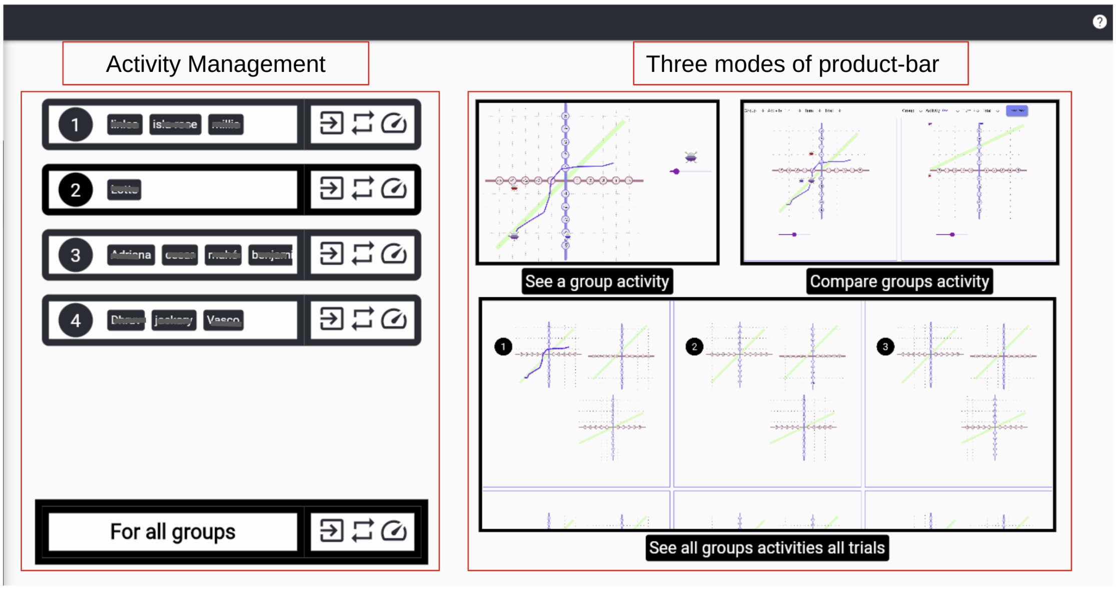


Figure 5.3: The main page of the CelloRoom 2.0 orchestration tool which consists of two main parts: 1) activity management 2) access to the three modes of the product bar. These functionalities are described in Section 5.2

- I added the possibility to *repeat* any activity for a certain group or the whole class, as shown in Figure. 5.4. This functionality was requested by teachers in the first iteration for making students that are waiting for the others to be occupied or in the situation

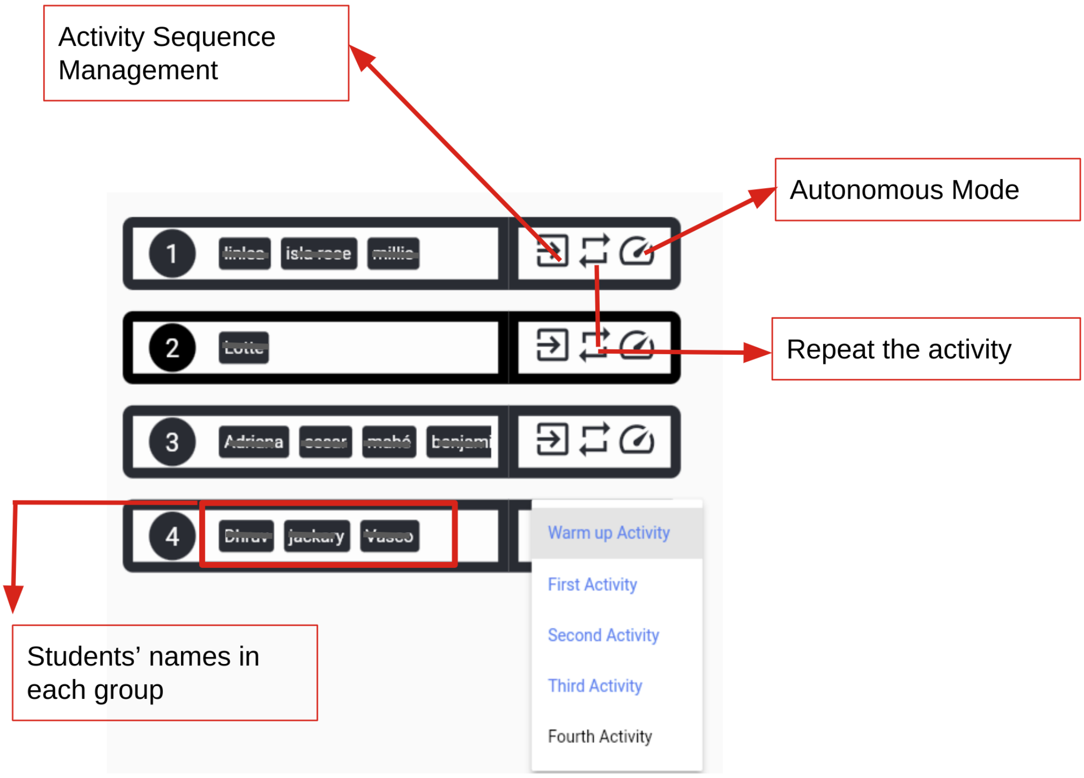


Figure 5.4: The activity management functionality in CelloRoom 2.0 consists of: 1) activity sequence management menu in which teachers can send a group or all groups to a selected activity 2) an option to repeat the current activity 3) enable/disable the autonomous mode

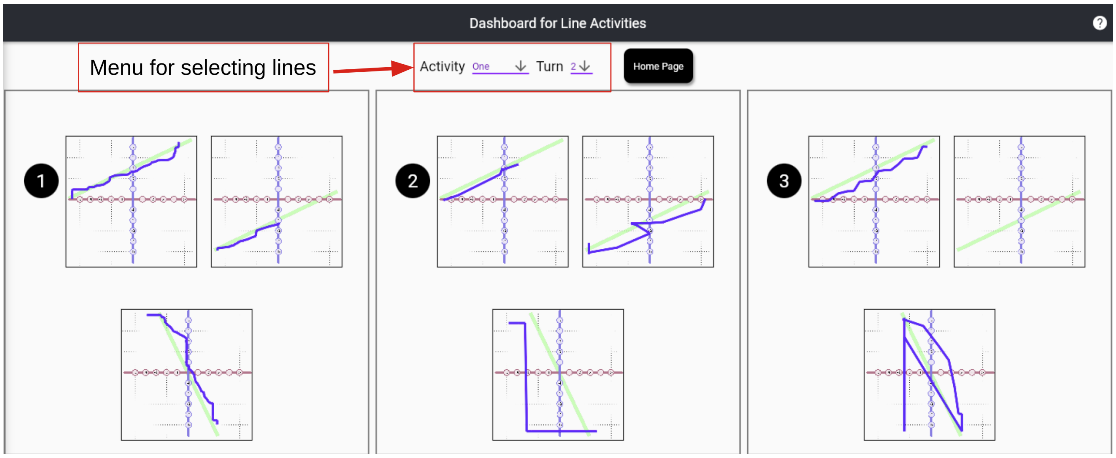


Figure 5.5: A snapshot of the CelloRoom 2.0 that shows groups' solutions (as defined in Section 5.1) in an aggregated mode (more details about this mode can be found in Section 5.2). The menu at the top of the page enables teachers to choose groups' solutions from different activities.

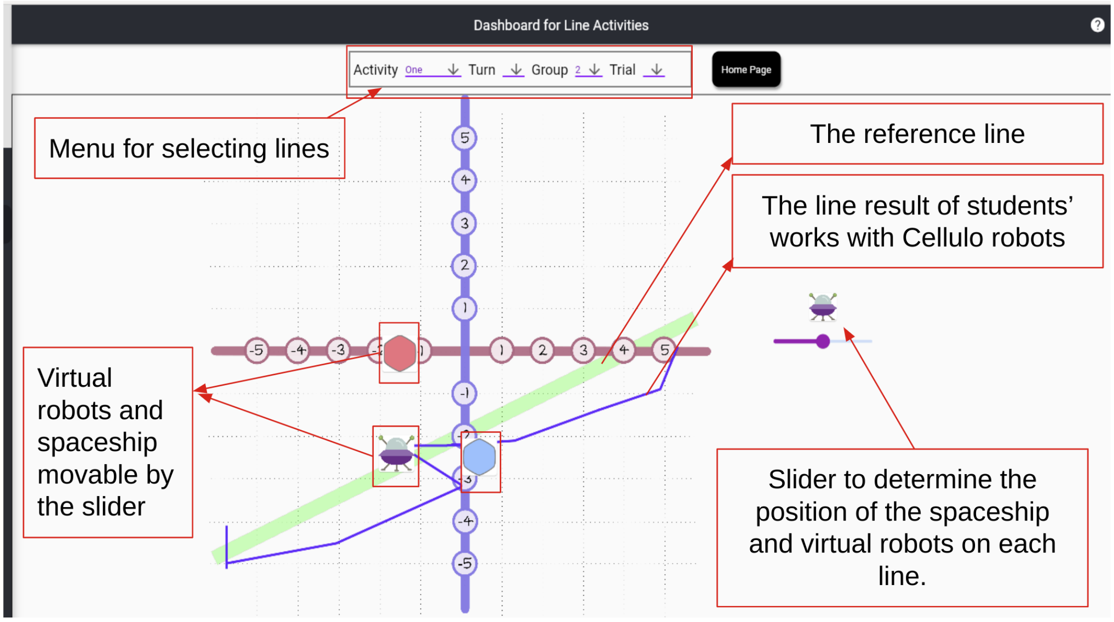


Figure 5.6: A snapshot of the CelloRoom 2.0 that shows a group's solution (as defined in Section 5.1) in the zoom mode (more details about this mode can be found in Section 5.2). The menu at the top of the page enables teachers to choose groups' solutions from different activities.

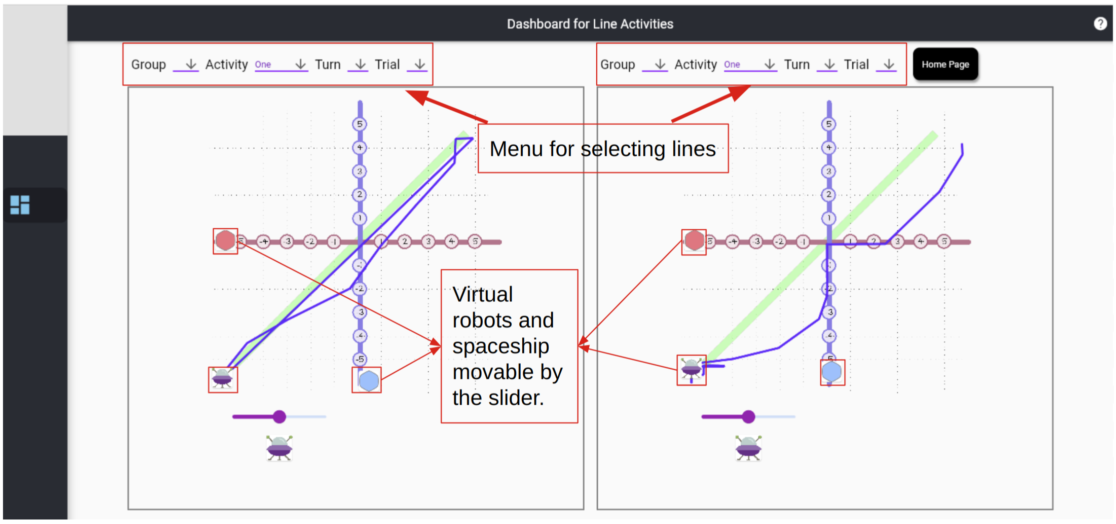


Figure 5.7: A snapshot of the CelloRoom 2.0 that shows two groups' solutions (as defined in Section 5.1) in the comparison mode (more details about this mode can be found in Section 5.2).

they decide to repeat an activity, e.g. because there was a problem with the activities in the first place.

- Adding the possibility for teachers to let students advance through the activities autonomously without teachers' step-by-step authorization, as shown in Figure. 5.4. This functionality was added in response to teachers' needs of letting certain groups advance on their own in the first iteration.

- I facilitated the possibility to access the three modes of the product bar by making it accessible from the main page of CelloRoom 2.0, for teachers, as shown in Figure. 5.3 (I explain the three modes later in this section). One of the issues I noticed in the first iteration of CelloRoom was that teachers had difficulty accessing the product-bar from the interface. With this update, teachers would have easier access to it.
- I added three different modes of the product bar, which are explained below, to elaborate on various possibilities to use the product bar. Also, instead of having textual visualization, showing students' scores in the activities in CelloRoom 1.0 (Figure. 4.7), graphic visualization were used. These updates were envisioned in order to increase teachers' usage of this functionality, with respect to CelloRoom 1.0, and its usefulness to enhance OPMD.
  - **Zoom**: projecting a group's activity on the beamer in class helps teachers in selecting a group's solution and share with rest of the class (Hatch et al., 2011; Stein et al., 2008). In this mode, teachers can show only a group's solution with a large size (as shown in Figure. 5.6), to talk about that specific group's work. To illustrate the movement of Red and Blue Cellulo robots along the axes and it's relation with the line slope, teachers could simulate the movement of virtual robots by interacting with a slider to determine the position of the virtual robots at various modes, as shown in Figures. 5.6 and 5.7.
  - **Comparison**: one of the important ways to create discussion in class is to compare students' activities (Do-Lenh et al., 2012), since it highlights the differences and uniqueness of each group's solution (Begolli and Richland, 2016). In this view, as shown in Figure. 5.7, teachers can compare groups' solutions with each other, which could be a rationale for sequencing students' solutions (Stein et al., 2008).
  - **Aggregated**: it's important to provide an aggregated view of all groups' solutions (Do-Lenh et al., 2012), so teachers can choose which group's solution to select for sharing. In this mode, *all* the groups' solutions in each activity and each turn are shown in a same page (as shown in Figure. 5.5) to provide an at-a-glance view for the teacher. This view also could be helpful to find the rationale for sequencing groups' solutions to be shared, for example by starting from the best group's work or the solution that is used by the majority of groups.

5.3 Participants and Data Collection

5.3.1 Participants

Five primary/secondary school teachers from schools across Switzerland volunteered to run the learning activities and use CelloRoom 2.0, however with different number of sessions,

Table 5.1: The detailed information about the teachers who participated in the experiments. (Teachers' names are assigned and not real)

	Number of Sessions	*Level*	*Gender*	*Number of total students (age-range)*
Albert	1	Primary	M	16 (10-11)
Brian	1	Primary	M	12 (9-10)
Caroline	2	Secondary	F	34 (12-13)
Diana	3	Secondary	F	47 (session 1: 12-13, session 2: 11-12, session 3: 10-11)
Edward	1	Secondary	M	9 (12-13)

as shown in Table. 5.1. The participants were recruited through convenience sampling, i.e. the experiment information was advertised through the network of local schools and later volunteer teachers contacted me to participate in the study. Teachers were encouraged to use the activities in as many sessions as they want. Each class had at least 9 students. All the teachers and students agreed to participate in the study with informed consent. Ethics approval for the study was obtained from the Human Research Ethics Committee (HREC) at Swiss Federal Institute of Technology Lausanne (EPFL), under reference number 018-2021. According to the ethical protocol, recording audio/video from classrooms was only possible upon teachers, students (if they are over 12 years old) and their parents' agreement. All teachers' names were anonymized and instead fake names (Albert, Brian, Caroline, Diana and Edward) are used for reference to teachers in this chapter. The goal of all sessions was to teach line slope, except in the case of Brian who, due to the lower age of students, only briefly touched the concept. All teachers were accustomed to manage technologies in their classrooms, like beamers for presentation as part of their teaching and tablets in their learning activities; however only one of them had prior experiences with any form of orchestration tool for management. In terms of teaching experience, Albert, Brian and Diana had prior experiences with ER before the experiment.

5.3.2 Procedure and Data Collection

At least two weeks prior to the first session, the main researcher presented the activities to each participating teacher, in a mock session, with a duration of 60-90 minutes. Teachers were asked to play the activities themselves, so that they would get a sense of what their students would experience later on. In this mock session, the researcher was playing the role of the teacher for two purposes:

1. Teachers would get an idea of how the session could go (although they were never obliged to repeat the actions the researcher did as a teacher).

2. Teachers would see how the CelloRoom 2.0 could possibly be used for classroom orchestration and especially creating discussions, as described in Section 5.2; the main researcher demonstrated the several pages of CelloRoom 2.0 interface, the functionalities, including the three modes of the product bar and mentioned possible conversations and questions with students. After this, teachers were asked to familiarize themselves with the CelloRoom 2.0 interface and could ask any question to the researcher. They were also provided with tutorial about how to use the functionalities of CelloRoom 2.0 in the format of presentation and video.

Pre-test, containing five questions, was performed before sessions 6,7 and 8 and after sessions 3, 4, 5 and 8, post-test was performed to measure the students' learning, containing eight questions related to the concept of line slope. Both tests were validated by teachers for clarity and coverage of concepts related to line slope. Since Albert and Brian anticipated that the learning activity would be higher than excepted level of students' knowledge, the pre and post tests were not performed in sessions 1 and 2. Due to lack of time, pre or post-test was not performed in sessions 3-7.

During the session, the researcher was present to answer possible technical questions the teacher could have about the robots (for example, whether they needed to change the robots, due to low battery or malfunctions). The teacher was allowed to ask any question, anytime, to the researcher, however the researcher was not in contact with students directly and only communicated with teachers in case they had follow-up questions. Teachers wore a microphone designed for recording lectures and interviews (Røde smartlav+ [I]) to record their dialogues and interactions with students. To complement the audio recording, a class video was recorded by a camera located at the back of the class. The class recording was not possible in the first session, according to the teacher's request and the class discourse was not recorded due to technical problem during the experiments.

After the session, the main researcher conducted semi-structured retrospective interviews with the teacher about the session, lasting around fifteen minutes. The goal of the interviews was mainly to collect teachers' perceptions about their usage of the CelloRoom 2.0 and possible usability issues and and also their opinions about the learning activity. To initiate the interview, teachers were asked about their opinion about the learning activity (e.g. *How students performed the learning activity?*, *Did it go according to your plan for the session?*). Then, to answer our research questions, the main researcher asked more detailed questions about the teachers' usage and usability of CelloRoom 2.0 (e.g. *Did you look at the groups' solutions in the dashboard? Was it helpful?*) and their intention (e.g. *What was your intention of using the product bar?*). The data sources and their analysis method is shown in Table. 5.2.

[I] https://rode.com/en/microphones/mobile/smartlav-plus

Table 5.2: The source of data and the corresponding analysis to answer the research questions

	What do they represent	Analysis Methodology
Semi-structured interview with teachers	- Teachers' opinions about the functionalities of CelloRoom 2.0 (RQ1)	1) Automatic speech to text 2) Thematic analysis to identify teachers' intentions for using CelloRoom 2.0, usability issues and teachers' opinions about the learning activity
Entire-class video recording	- Teachers' usage of CelloRoom 2.0 (RQ1)	Counting the number of times teachers were interacting with the robot failure alert, activity sequence management and product bar
Teachers' speech activity recording	- Link between teachers' interactions with CelloRoom 2.0 and one of the three key practices of Stein et al.'s framework (Stein et al., 2008 (RQ2))	Categorizing teachers' interaction with CelloRoom 2.0 w.r.t one of the three practices of OPMD (selecting, sequencing, connecting) by Stein et al.'s framework (Stein et al., 2008). More details about the procedure can be found in Section 5.3.2

5.3.3 Data Analysis

Teachers' opinions about CelloRoom 2.0 and learning activities

For analysing the interviews, firstly, the interview audio files were transcribed to text using Otter.ai, a speech-to-text application[II]. The data was analyzed according to Clarke et al.'s process of thematic analysis (Clarke et al., 2015):

1. I listened to the interviews to get familiar with the teachers' responses to the questions.
2. I defined the initial themes according to the functionalities of CelloRoom 2.0 (Robot failure alert, activity management and product bar)
3. I searched for themes according to the initial codes in the notes by inductively grouping the notes into larger and larger categories based on similarities.
4. In addition to finding notes related to the three initial themes, I also found notes related to the teachers' opinions about the learning activity. I reviewed the entire data set to ensure that all the notes are matching the already-assigned themes.
5. The names of themes remained as same as the initial ones. The relation between the analysis and the main research questions is mentioned in Table. 5.2. In the results

[II]https://otter.ai/home

section of this Chapter, examples of teachers' interviews are provided for more clarity.

6. To ensure the validity and reliability of the analysis, 30 percent of the data was coded by 2 researchers (me and another expert qualitative researcher) and the categorization was refined until one-hundred percent agreement was reached. Thereafter the rest of the data was coded by me.

Afterwards, one member of the research team verified the automatic transcript to correct existing errors. The interviews were clustered to understand teachers' intentions of using the functionalities of CelloRoom 2.0 and its usefulness. Also their comments about the usability issues of the tool were all noted.

Class timeline

The classroom discourse was annotated using ELAN (a professional tool to manually annotate and transcribe audio or video recordings)[III] to delve deeper into the usage and effects of the proposed orchestration tool. The researcher segmented the class time into the following categories:.

- *Logistics*: includes all teachers' efforts to setup the activity, including the group management or technical management (setting up the robots, tablets and physical maps).
- *Pre-activity, Introduction*: includes all teachers' efforts to introduce the learning activities, i.e. to explain what tasks are students supposed to do.
- *Exploration*: includes all teachers' interactions with the students while they are playing the activities, to answer questions and make sure the students play the activity as intended.
- *Discussion*: includes all teachers' efforts to engage the students in a reflection on their experience of playing the robot-mediated activity and connecting to the learning goals. The discussion normally happens in a group/class level initiated by the teacher.

Usage and Usefulness of CelloRoom 2.0

The usage of robot failure alert and the activity sequence management functionalities in CelloRoom 2.0 were extracted by the script running on the CelloRoom interface, counting these values. In addition, regarding the robot failure alert, after each failure, teachers' reaction was noted in one of the three following cases:

1. **Noticed from the alert** teachers noticed the alert from CelloRoom and changed their course of action to go assist the group with the failure.

[III] https://archive.mpi.nl/tla/elan

2. **Validated by the alert** teachers were notified of the failure from the group and then looked at CelloRoom to validate if their claim was true.

3. **Did not use the alert** teachers were notified of the failure from the group and did not look or use the CelloRoom.

To assess the usage of the product bar in CelloRoom 2.0 and its usefulness regarding OPMD, the class recording was analyzed to note each time a teacher interacted with the bar on beamer. Each interaction period starts with the teacher looking at or touching the interface of the dashboard and finishes when they move away to be engaged in another activity, e.g. going around the class. Each interaction was labelled to denote the teachers' OPMD practice it supports (if any) (Stein et al., 2008), under the following criteria. Due to the high level of the reliability of this analysis on my personal bias and avoid the researcher-bias in the data analysis, firstly one of the eight sessions was annotated by me and an expert for qualitative analysis.

- **Checking** if during the interaction teachers only look at groups' solutions and don't make any conversations with students. This action is similar to monitoring in Prieto et al.'s framework of orchestration (Prieto et al., 2011), where teachers only want to have an overview of the progress of the whole class or for a specific group.

- **Selecting** if during the interaction teachers publicly talk about a group's solution publicly using the product bar.

- **Sequencing** if during the interaction teachers sequence the sharing of groups' solutions publicly, using the product bar, following a rationale to move from one solution to another. The rationale could be explicitly stated by the teacher of inferred by their conversations with the students or the order in which they display solutions.

- **Connecting** if during the interaction the conversation of the teacher with students includes sentences that are related to the learning goal. In line with the definition of connecting practice (Stein et al., 2008), I assume that a conversation related to the connecting practice should involve *both* words related to the ER-enhanced activity and the learning goal. Thus, we performed a two-step evaluation:

  1. I created two pools of words that could be used by teachers, one related to the robot-mediated activity and students' solutions and one related to the learning goals. These words were selected according to the definition of the learning activity an it's objective, mentioned in Section 5.1.

     The activity-related words are: red (X) or blue (Y) axes, robot, Cellulo, line, drawing, graphs, movement, map coordination, tablet, activity, teamwork, communication, cooperation; and the learning goal-related words are: math, slope, intercept, gradient, X or Y axes, rate of change or its equivalent in curriculum (e.g. rise over run, time over distance), speed, fast(er), slow(er), steeper, equation, start point, end point, straight, horizontal, vertical, perpendicular, diagonal, parallel. Some words were shared between the two pools, e.g. *line*. In that case, depending on the context, the word would be categorized as belonging to one or the other pool, e.g. if the line refers to the one that students draw with their robots, it is considered as an activity-related word, while if the word line refers to the abstract concept of lines, it is a learning goal-related word. I manually filtered interactions into conversations that included at least one word from each pool.

2. To make sure the appearance of words from the two above-mentioned pools in the conversation was not random, the main researcher verified each conversation manually.

5.4 Results

5.4.1 How did the sessions go?

Figure. 5.8 shows the timeline for the eight experimental sessions, which took on average 55 ± 12 minutes and Table. 5.3 shows detailed information about the distribution of class time per management category (intro, exploration, discussion and logistics). In general, teachers started the session with an introduction of the goal of the session, the robots and the activity rules, for example explaining the three roles that students would play in the activity. For the initial technical setup, each group had to go and receive two robots and a tablet from the main researcher. The maps were already placed on the groups' tables by the teachers before starting the sessions. Afterwards, teachers would explain the login process on the tablets and monitor each group in the process by going to their desks. Teachers were guiding the students to advance through the activities one by one synchronously or asynchronously. All teachers orchestrated discussion moments, some only at the end of the session, while others also made between-activity discussion.

Except Albert, the teachers expressed a positive feeling about the sessions. They mentioned that the session was beneficial as children got excited about learning mathematics. In this regard, Edward said: *I never got those kids to be so much excited about what they're doing, which is great! That was actually my purpose.* On the other hand, Albert emphasized that due to the novelty of the activities, he faced some difficulties: *I noticed at the beginning that it was not really going smoothly. It was taking too much time for them to understand the objective, and I was asking myself, What did I say wrong? Did I miss something?*. Even if other teachers were not bothered as much as Albert about this issue, they did express the same opinions about the effect of inexperience in teaching the robot-mediated learning activities on their management quality.

5.4.2 Teachers' Opinions about the Learning Activities

Teachers had opposing feed backs about the learning activities: Brian and Diana thought their students could make connections between the activities and their learning goal. They found the elements of collaboration, visualization of mathematical ideas thanks to the robots, and consistency with current pedagogy in schools as main advantages of the learning activities, as Diana said:

> *I think [the learning activities] are very consistent with the current pedagogy in mathematics, in the way we teach a straight line. One of hard things to teach is the notion of independent variable whether it is in direct or indirect proportion to the dependent variable. So that vocabulary doesn't come out normally. And I like here to see that vocabulary came out because then that applies directly to other lessons, like physics or chemistry.*

Brian found the activities as a great consolidation step for his future teaching and he suggested to use the structure of activities for teaching other topics, like the geographic coordinates system (longitude, latitude). Despite some teachers' interest, others doubt the benefit of the learning activities on learning line slope for children. Caroline thought these activities are even making the topic harder for students as she said:

> *[In the activities] you're asking students to [move their robots] separately. I'm just wondering how that helps them understand [the equation of a line] (y equals mx plus c), if they're moving it separately. I was trying to bring their attention to the relative speed [of two robots], how fast you need to go compared to other robot, but I think If they find this a difficult topic anyway, bringing in an element of complication would not help! I found that they could have lots of fun with the game and play with it and get good, but then taking that back to understanding that concept, I'm not convinced by the links. I ask myself how much have they learned for their exam?*

When teachers were asked about students' strategies in the learning activities, three type of students' mistakes were reported:

- **Not using mathematical language in guiding their friends** One of the envisioned learning activities' goals is for the guider person to use words like speed, faster, slower or coordinates to guide the movement of robots, however teachers reported that one common students' mistake was to not use this terminology in the guidance, as Brian said: *Some of them were using the person's name, instead of X or Y axes [to guide their friends], because it showed me that the others really didn't recognize what X and Y are.*
- **Not moving the robots along the axes** The blue and red sidebars on the physical map are supposed to represent the axes that students can move their robots on (see Figure. 5.1). This was especially designed so that students draw the target line by moving the robots along the two orthogonal axes, however they sometimes moved the two robots along the line, which is not the purpose of the activity (shown in Figure. 5.9), as Caroline said: *The first group was just moving the robots along the line rather than along the axes.*

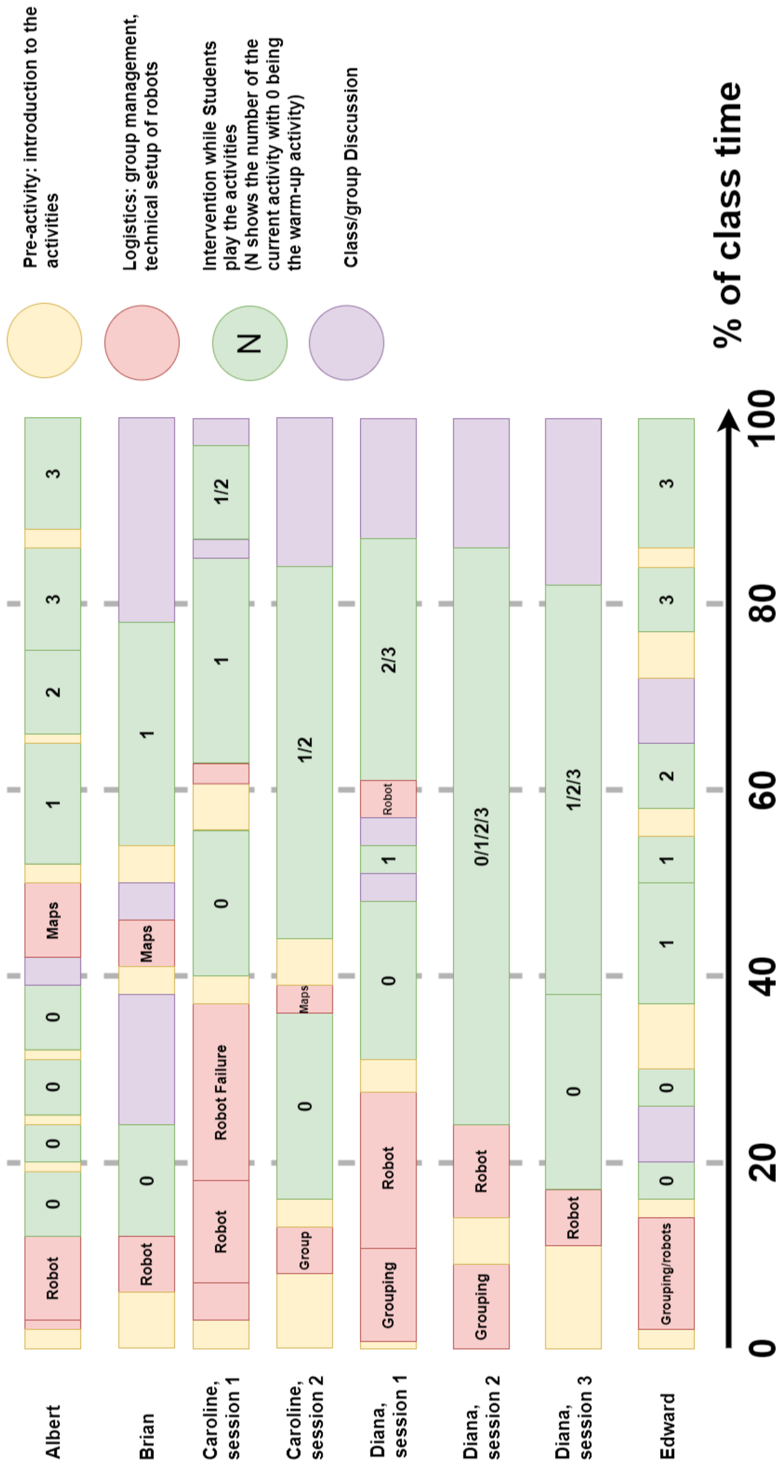


Figure 5.8: The comparison of timelines of teachers' actions in their sessions highlights similarities and differences between their activity management patterns.

Table 5.3: Distribution of sessions time among different categories (in percentage)

	Intro	Exploration (playing the activities)	Discussion	Logistics
Session 1 (Alert)	9	62.6	3	25.4
Session 2 (Brian)	14.3	35.2	39	11.5
Session 3 (Caroline)	10.5	47.4	4.5	37.5
Session 4 (Caroline)	16.5	59	16	8.5
Session 5 (Diana)	1.3	45.8	18.4	34.5
Session 6 (Diana)	5	60.5	14.7	19.8
Session 7 (Diana)	10.7	65.3	18.2	5.8
Session 8 (Edward)	23.2	52.5	12.7	11.6

- **Using the robots LEDs for guidance instead of listening to the guider** The LED light on Cellulo robots were supposed to be an extra guidance for the Blue and Red players to know if they are following the line correctly. However for some groups, this feedback was used in place of the guider which was not supposed to happen. This mistake could actually hinder the role of guiders and their learning tasks, as Brian said: *If you turn the lights off, then it forces them to actually listen to the guider.* As an alternative solution, he suggested the idea that this could be an option under teachers' control: *I see it more like levels. For example, they can repeat the same activity with and without lights and see what happens. I think [having no lights] would really force them to collaborate and then I can do a little discussion and ask then Did you have more problems without the lights? What made it difficult? and why?*

5.4.3 Teachers' usage of CelloRoom 2.0 and its usability and usefulness

Robot Failure Alert

Table. 5.4 shows the number of failures in each session and how much the alert was used by teachers for notification and validation. Overall, it was mostly used for notification rather than validation and teachers changed their course of action, thanks to the alert. No failure was noticed that in which teachers did not use and benefited from the alert information. According to the interviews, all teachers confirmed the advantage of using the alert, as Albert said: *The feedback that the robot wasn't working was coming from the dashboard. I can see it right away, because it goes red at the top. So that worked well.*

Table 5.4: Teachers' usage of the robot failure alert in CelloRoom 2.0

	Number of robots	***Number of failures***	***Noticed by the Alert***	***Validated from the Alert***	***Did not use the alert***
Session 1	10	5	4	1	0
Session 2	8	0	0	0	0
Session 3	10	1	0	1	0
Session 4	12	2	1	1	0
Session 5	12	3	2	1	0
Session 6	10	2	1	1	0
Session 7	8	0	0	0	0
Session 8	6	0	0	0	0

Activity Sequence Management

Teachers used this feature every time they needed to move the students between activities (to move the entire class or just a group). Table. 5.5 shows the activity management preferences for each teacher, which shows teachers mostly preferred to manage their activities asynchronously. I realized this choice mostly come back to teachers' managing preference rather than class conditions, i.e. for those who had more than one session, they keep the same pattern, for example Diana was managing the class asynchronously in all her sessions. Teachers preferred to have the control over students moving between the activities (no teacher used the autonomous mode). However the functionality to repeat the activity was found helpful as teachers needed to repeat the activities mainly for groups who did not succeed to run the activities (The number of usages in each session is shown in Table. 5.5).

Product-bar

Table. 5.6 shows the teachers' usage of the product bar in each session. Albert is the only teacher who never used it, motivating his choice with his preference for giving more time to students to play the activities. In this regard, he said: *I didn't really decide to use [the product bar]. Because I was late and I really wanted to speed up.* Table. 5.7 shows which modes of product bar were favored by teachers; as expected the zoom mode was used for selecting, which seems reasonable because teachers want the group's solution to be visible in large dimension to everyone in the class. The aggregated mode of the product bar was both used by teachers to check group's progress and select a group's solution, however surprisingly comparison mode was never used. Among these selecting occasions, Caroline (in session 3) and Diana (in session 6) used the opportunity to also connect the group's work to the learning

Table 5.5: Teachers' usage of the activity sequence management functionality in CelloRoom 2.0

	Teacher	***Asynchronous /synchronous***	***Number of repeating the activity***	***Number of usage of the autonomous mode***
Session 1	Albert	Asynchronous	2	0
Session 2	Brian	Synchronous	0	0
Session 3	Caroline	Asynchronous	0	0
Session 4	Caroline	Asynchronous	1	0
Session 5	Diana	Asynchronous	2	0
Session 6	Diana	Asynchronous	1	0
Session 7	Diana	Asynchronous	2	0
Session 8	Edward	Synchronous	1	0

goal. The following conversation from Caroline is an example of a selecting practice followed by a conversation related to connecting practice:

> *Let's have a quick look at some of these graphs that we've drawn guys. If we have a look, we can see some of the groups like this group [which] have done a really good job of drawing.*

Afterwards she continued the discussion, connecting the group's solution to the learning goal by direct instruction:

> Caroline: *Who's group five? Could you give us any tips? What did you do?*
> Student 1: *I looked at the robots as well to see the color on the robot, if it's red or yellow. I was telling them to go slower or faster and where they need to finish or where they need to start.*
> Caroline: *Brilliant. And where were you moving your robots?*
> Student 1: *on the blue [and red] axes.*
> Caroline: *Excellent! on the red and blue lines along the side, that's where we're trying to move our robots. So the idea is saying whether the robots need to be moving at the same speed or different speeds depending on what angle or slope our line is.*

Almost all teachers (except Albert) sequenced sharing groups' solutions mostly from the first to last group in the class (except Caroline who compared two groups only). For example, Brian first started asking students' opinions about the first group's work:

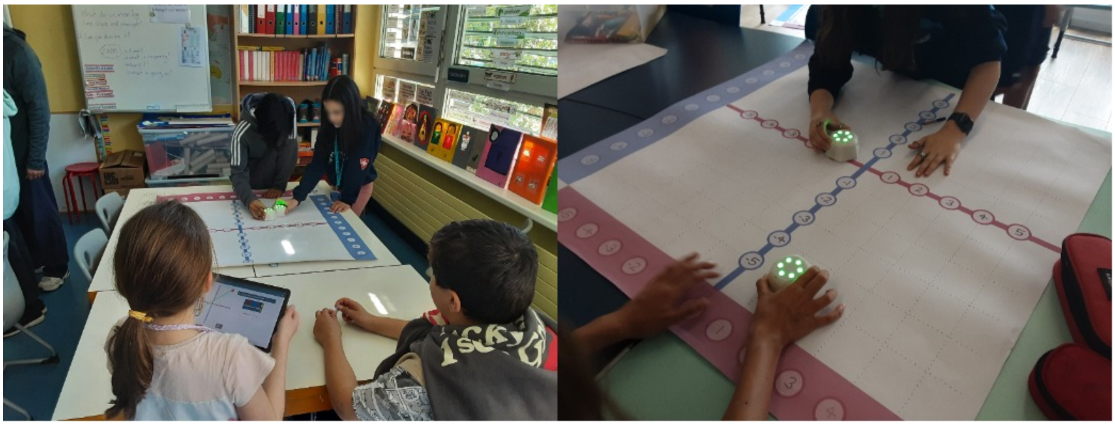


Figure 5.9: Snapshots of students' activity demonstrating a common mistake in performing the learning tasks, as reported by teachers. Left: two students moving both robots along the target line, Right: Red and Blue players don't move the robots along the relevant sidebar, but moving it in the middle of the physical map.

> Teacher: *Here, we're going to see your results. And this is the warm up activity and group one. Okay, ready? What do you think about group one here so far?*
> Student 1: *They tried like us by first going up and then using the axes.*

Then, he continued the conversation moving on to other groups' solutions.

Four types of intentions to use the product bar emerged from the interviews with teachers, as follows:

- **To track students' progress**. Teachers mentioned using the product bar to see all groups' works, as Diana said: *[I used the dashboard] to see that everyone had done three turns, that everybody had a chance to try it and to see where they were. Because I realized one group was moving much faster. I used the dashboard, also to keep track of where everybody was. It's interactive. It's really intuitive. I liked it.*

- **To check the quality of a group's solution**. Teachers highlighted as important that they could monitor the quality of the groups' solutions, rather than only knowing that they finished the activity, as Diana said: *How do I know that they really have done the activity correctly? All I know is that they drag some robots across their maps and then say I'm done, unless I see the lines. I don't know that you've done it. I like evidence.*

- **To initiate discussions**. Brian stated that the presence of students' results in the product bar is the reason to use it for creating discussion, as he said: *I like the dashboard to show the results, and it's a great way to talk in discussion.*

- **To engage students**. Some teachers were using the product bar to motivate their students. This was done by selecting a group with high performance and then admiring

Table 5.6: Teachers' usage of the product bar for checking and the three practices of OPMD

	Teacher	***Checking***	***Selecting***	***Sequencing (The rationale)***	***Words observed in connecting conversation***
Session 1	Albert	0	0	No	No
Session 2	Brian	0	8	Yes (by going over all groups one by one)	No
Session 3	Caroline	1	4	Yes (comparing two groups)	Graphs, robots, same or different speeds, line slope, angle.
Session 4	Caroline	4	0	No	No
Session 5	Diana	3	8	Yes (by going over all groups one by one)	No
Session 6	Diana	3	5	Yes (by going over all groups one by one)	Line, faster, steeper
Session 7	Diana	2	1	No	No
Session 8	Edward	1	6	Yes (by going over all groups one by one)	No

the group's solution publicly, as Edward said: *From the very beginning, I pointed on one group [solution] saying: look, that's so beautiful! and they were saying let us also do something like that.*

5.4.4 Usability issues

Some usability issues were extracted from teachers' feed back in the interviews:

- Teachers complained about the complexity of choosing the line from a specific group since they had to choose it from the selection menu (see Figure. 5.5), and they especially asked for the menu selection to be simpler, i.e. instead of requiring three parameters of the name of activity, the turn and trial in the selection menu, as shown in Figure. 5.6), to choose the line it would be done with one parameter (for example with an unique code for each line).

Table 5.7: Teachers' usage of the product bar in the three modes of presentation (aggregated, zoom and comparison)

	Aggregated	*Zoom*	*Comparison*
Checking	14	0	0
Selecting	23	9	0

Table 5.8: Comparing the two versions of CelloRoom in terms of teachers' usage of each functionality

Functionality	***CelloRoom 1.0***	***Update***	***CelloRoom 2.0***
Progress bar	Used in limit	Removed	
Robot failure alert	Used extensively	No change	Used extensively
Activity sequence management	Used extensively	Adding the functionalities of 1) To repeat the activity, 2)Let students be autonomous	Used extensively from the two new functionalities, only the repeat one was used.
Product bar	Used in limit	Adding three modes of product-bar Make it accessible from the main page	Used extensively

- Diana found the naming for the different modes of the product bar on the main page of the interface, as shown in Figure. 5.3, confusing as she said: *I didn't understand the wording. Because for me to see all group, all activities, all trials, I thought that was going to show me all of activities of group one. Then group two, all of the activities, group three, all of their activities and so on.*

- Caroline wanted students' names to be displayed instead of/ along with group numbers in all modes of the product bar, as shown in Figures. 5.5 and 5.6. In this way she could more easily map the information found on the product bar to the physical location in the class, i.e. if she finds a specific solution interesting and wants to talk with the group, she could easily identify them in the class.

5.5 Discussion

The aim of this study is to evaluate teachers' usage of CelloRoom 2.0, its usability and usefulness, especially for OPMD in robot-mediated classes. Based on these results, in this section, I firstly compare the usage and usefulness of CelloRoom 2.0 in respect to CelloRoom 1.0 and later discuss whether teachers' usage of the product bar supported the practices of OPMD (Stein et al., 2008). I also outline key lessons learnt from the studies in Chapters 4 and 5 in the

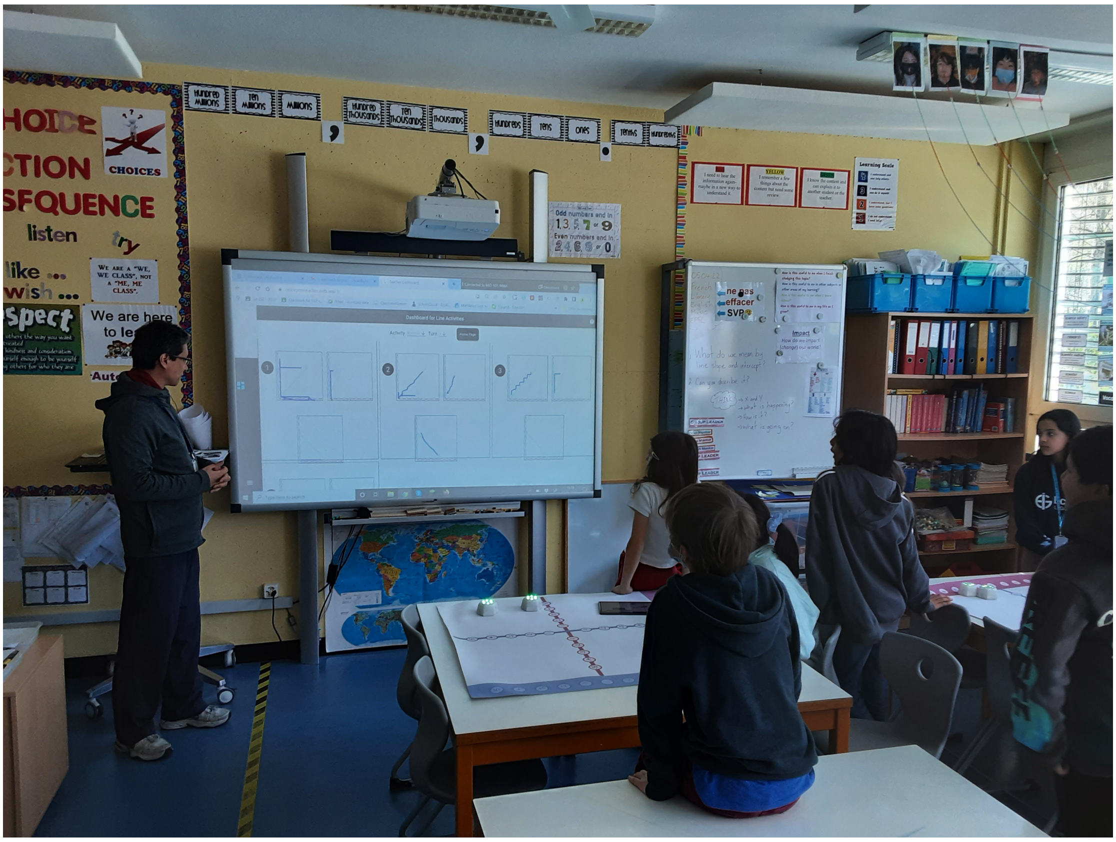


Figure 5.10: A view of the class in our case study in the class discussion moment. The teacher and students are looking at the aggregated mode of the product bar.

form of design guidelines for orchestration tools for robot-mediated classrooms.

5.5.1 CelloRoom 2.0 vs CelloRoom 1.0

Table. 5.8 compares teachers' usage for each orchestration functionality present in the two versions of CelloRoom, whose iterative design and evaluation is reported in Chapters 4 and 5 of the thesis. The robot failure alert and activity sequence management were used in a similar way among the two versions. According to the goal of robot failure alert to increase teachers' awareness about robot failures, this goal was almost achieved in the studies for both versions (all teachers in CelloRoom 2.0 and five out of six teachers in CelloRoom 1.0 used the alert). Similarly, the activity sequence management was used in both versions to manage the class and give to teachers the flexibility of controlling the activity sequence synchronously or asynchronously. The main difference between the teachers' usage of a functionality in the two versions of CelloRoom was observed for product bar in the second study; not only this functionality was used for creating discussion, which was envisioned, but it was also used for monitoring students' progress (called checking in Table. 5.6), which was not excepted. The difference in usage of product bar between the two versions could be explained for two reasons:

- With respect to the progress bar in CelloRoom 1.0, the product bar in CelloRoom 2.0 shows the students' solutions rather than merely providing information on whether students have accomplished a certain task in the activities. According to teachers' interviews, this feature can show the *quality* of the students' solution, which they prefer over measures indicating *quantity*.
- With respect to the product bar in CelloRoom 1.0, the one in CelloRoom 2.0 is more appreciated, since it allows for group's solution to be more easily evaluated by teachers: in CelloRoom 2.0, the group's solution is a visual element showing the line drawn by students' robots compared to its target while in CelloRoom 1.0 the information is a textual element showing students' scores, e.g. that they collected twenty stars in one minute.

5.5.2 Design Implications

Based on the results of two iterations of CelloRoom (described in Chapters 4 and 5), a number of recommendations for designing orchestration tools for the context of in-person robot-mediated classroom in primary school can be drawn:

1. In terms of indicators for providing awareness, both in-depth indicators (such as the *product bar*) and generic ones (such as the *progress bar* in this study) seem necessary, however the usage time seems different. In-depth indicators allow teachers to motivate students in improving their performance and thus support them in creating rich and engaging discussions *after* the learning activities, while generic ones provide light information *during* the learning activity to make timely decisions, like transition from an activity to the next. Two specific factors were found to demotivate teachers from using awareness visualizations: 1) strong student-teacher communication which makes generic indicators unnecessary. 2) the fear of unhealthy competition and chaos in class which make teachers doubt about sharing in-depth indicators that might rank students in their performance.
2. Robot failure alerts can help teachers prioritize assisting groups in need and also act as a reliable source of information concerning the status of the robots in the class. CelloRoom acted as a monitoring source for teachers notifying them after the failure, however research on orchestration tools has indicated the teachers' need to be guided by the tool about which action to take (van Leeuwen et al., 2019). Guiding teachers via orchestration tool especially becomes more important when the robotic platforms are technically more complex. For example, what if instead of only robot being the source of the failure, the tablet or other parts of the activity (e.g. the cable for connection between the robot and computer or mechanical parts of the robots) could also be the source of

failure? In that case the tool should help teachers in *debugging* the source of failure with information about the action to fix the failure (for example, to change/charge the robot). Also the tool might support teachers to *predict* the failure (e.g., alerting teachers that the battery of the robot for one of the groups will die in less than 10 min), so teachers have time to prevent the failure.

3. Concerning the management of the activity flow, it is important to provide teachers with multiple options for activity transition and its parameters, so that: 1) they could freely choose the activity sequence management approach best suited for their students 2) they could control the difficulty level of the activities, for example in the activities with Cellulo robots, teachers mentioned their interest to enable or disable the LED guidance for students, depending on their level of competence.

4. We re-emphasize the necessity of adapting the technology of the orchestration tool according to the teachers' orchestration behaviours for taking orchestration actions and for informing them about urgent class events, as has been mentioned in similar works (Alavi et al., 2009; Holstein, Hong, et al., 2018). For example, teachers like to go around during the activities and pay attention to students' conversation with each other or look at their interaction with the robots (especially since robot-mediated activities provide an easy-to-monitor situation, compared to screen-based activities). Therefore orchestration tools should be accessible from anywhere and not require teachers' attention constantly. In this case, wearable orchestration tools, like smart watches, can be promising (Quintana et al., 2016).

5.5.3 Lessons learned from the usage of orchestration tools to support OPMD

According to the results, teachers used the product bar extensively to *select* and *sequence* students' work to share publicly. Two teachers also went further and connected the students' works to the learning goals. Most of the teachers' interactions with the product bar were devoted to the selecting practice (Stein et al., 2008) as publicly sharing a group's solution, which is in line with similar findings from literature (Hatch et al., 2011). However, I noticed a difference in the intention behind the selecting practice as performed by the teachers involved in this case study and its goal in the framework of Stein et al., 2008; teachers' interviews suggest that their main intention for selecting was to engage students which aligns with Do-Lehn's results of teachers' usage of TinkerBoard (Do, 2012), while the core idea of the selecting practice in the framework of Stein et al., 2008 is to raise mathematical ideas.

Teachers mostly sequenced sharing students' solutions with the rationale of going over all groups in the class, one by one. We assume the intent for this sequencing is to make sure all students participated in the discussion, with no bias in prioritizing some specific groups. However, the rationale for the sequencing practice found in literature is to compare students' solutions, for example in TinkerBoard (Do-Lenh et al., 2012), with the purpose of creating competition among students.

Contrary to the relation between teachers' usage of the product bar and the selecting and sequencing practices, I found that only few interactions supported the connecting practice. Based on teachers' opinions, they mostly preferred to use the product bar for initiating the discussion, while only two teachers also continued using it for connecting students' works to the learning goals.

Reflections on this study allowed me to identify two important lessons for the purpose of supporting OPMD practices.

- Simplicity in choosing a group's solution is key. One possible factor in the design of the product bar that can increase the number of interaction with it and consequently support more selections could be to make choosing groups' solutions simpler. As an example, the teachers should be able to project a group's solution on the beamer by simply entering a unique code for each line, shown on the students' tablet, in the selection menu. The difficulty of interacting with the selection menu could be the reason why Diana and Caroline reduced the number of usages for selecting over sessions (see Table. 5.6). Improving the design might also lead to an increase in usage of the other modes of product bar, namely the zoom and comparison modes (see Table. 5.7).
- I did not observe a strong usage of the product bar and the connecting practice in this study, however the study design does not allow me to conclude whether this is due to the design of the product bar or teachers' teaching style. According to the results and also similar works in literature (Do, 2012), it seems that teachers perceive sharing the students' data for class discussion more as a tool to engage students rather to emerge mathematical ideas. In this regard, the emerging research question is that do teachers need support in connecting practice that can be addressed by orchestration tools? Further studies are required for understanding teachers' needs in this practice and also other practices of OPMD. Such studies should consider the challenges teachers face while performing these practices, which can potentially be supported by orchestration tools.

5.5.4 Limitations

Firstly, Due to the difficulty of the logistics of running experiments within the constraints of a tight classroom schedule, it was not possible to perform the pre and post test in all sessions. So, I was not able to see the effect of the proposed robot-mediated learning activities on the students' learning gain. Even if the data available, as has been provided in Chapter 4, due to numerous factors variant among the sessions (e.g. different ages of students, different teaching style, etc), drawing relationships between the different orchestration styles of teachers and the students' learning gains has been impossible.

Secondly, some of the students in the experiments have already being exposed to the learning goals (in Chapters 4 and 5) prior to taking part in the experiments. The results might thus change if teachers use this activity as an introduction, rather than a consolidation of the learning concept.

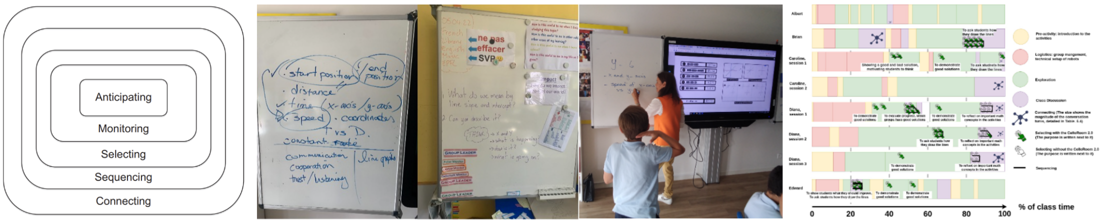
Lastly, the researcher was present during the class to provide technical help to the teacher, upon request. Studies without the presence of a researcher should be conducted, to ensure a greater ecological validity of the findings.

Implications of this chapter

The goal of this chapter is to evaluate the usage, usability and usefulness of the second version of CelloRoom, called CelloRoom 2.0, for constructivist teaching in robot-mediated classrooms by evaluating the role of the product bar functionality for the orchestration of productive mathematical discussions (Stein et al., 2008). Comparing to similar works in literature, e.g. TinkerBoard (Do, 2012), that explore the benefit of orchestration tools for class discussion, I looked more precisely at teachers' usage (categorizing it according to Stein's framework (Stein et al., 2008)) rather than its end-effects (e.g. on students' engagements).

I compared the results of usage and usefulness of CelloRoom 2.0 with the ones of CelloRoom 1.0 and provided design implications for orchestration tools for robot-mediated classrooms. In general, the results showed teachers' usage and positive attitude towards CelloRoom, plus its usefulness for selection, an important practice in OPMD framework. However some usability issues might have prevented further usage of the tool for OPMD. Based on the gaps observed between teachers' usage and OPMD, I realized that further analysis are required to understand teachers' challenges in the practices of OPMD, which I expand on in the next chapter.

6 Teachers' Needs in Orchestrating Productive Math Discussion



6.1 Introduction

Concerning the second research question and the research methodology of the thesis (design based research), each iterative cycle includes a reflection phase, which is described in this Chapter. After discussing the potential and drawbacks of the product bar in CelloRoom 2.0 for Orchestrating Productive Math Discussions (OPMD) in the previous chapter, this chapter takes a step further in reflecting teachers' practices in OPMD in the context of robot-mediated classrooms. While in the previous chapter I only looked at teachers' interactions with CelloRoom 2.0, in this chapter I look at their OPMD practices when orchestrating the session (regardless of their relation with the usage of CelloRoom 2.0). My motivation roots itself in the results of the previous chapter regarding the necessity of studying the teachers' practices in OPMD to further understand teachers' needs (and whether they can be supported by orchestration tools.

6.2 Data Analysis

The analysis presented in this chapter relies on the same data set of the experiment in Chapter 5, hence, the participants, experiment procedure and data collection remain the same mentioned before. The data used here includes teachers' speech activity and the entire-class video recording of seven out of eight sessions. In this section, I explain the data analysis procedure I adapted with the goal of extracting evidence of each of the OPMD practices in teachers' behaviours, according to the relevant definitions from Stein et al.'s framework (Stein et al., 2008), which relies on the annotation of the collected multi-modal data with a coding scheme. The data was analyzed according to Braun and Clarke.'s process of thematic analysis (Clarke et al., 2015):

1. I listened to teachers' speech activity and watched the entire-class video recording to get familiar with the teachers' OPMD.
2. I defined the initial themes according to the relevant definitions from Stein et al.'s framework (Stein et al., 2008) (Monitoring, selecting, sequencing and connecting).
3. I searched for themes according to the initial codes in the notes by inductively grouping the notes into larger and larger categories based on similarities.
4. The names of themes remained as same as the initial ones. In the results section of this Chapter, examples of teachers' speech activities are provided for more clarity.
5. To ensure the coding reliability, the data of one session was first jointly annotated by me and an expert in qualitative analysis, discussing and refining the coding scheme until we reached an agreement.

I then used the agreed-upon refined coding scheme to code the remaining sessions. The coding scheme includes criteria for identifying instances of each practice and whenever possible one or several quantitative indicators for each practice to quantify the enactment of the practice in each session, which are explained below:

- **Monitoring:** The goal of monitoring is to pay attention to students' mathematical thinking (Stein et al., 2008). In this regard, as criteria for identifying instances of this practice, I considered each teacher's conversation with a group as a monitoring attempt if it was related to one or more of the learning tasks (explained in the Section 5.1.1), via the following rules:
  - *Robots should move at a same time:* If the conversation relates to how the two robots should move relative to each other (e.g. should they move at the same time or not?).
  - *The relative speed of robots should be proportional to the slope of the line:* If the conversation relates to the relative speed of robots (by words like slower, faster) and also relates to one or both of these topics: 1) how the guider should guide the teammates 2) the slope or steepness of the target line.
  - *Robots should move, orthogonal to each other, along the Cartesian axes:* If the conversation relates to where robots should move on the map (e.g. whether they should be on the sidebars or whether they should not move in the middle of the map.)

– *Guider should recognize the roles of robots in X and Y directions correctly:* If the conversation relates to how the guider should give guidance to the two teammates with the robots, regarding the order of axes in which they have to move their robots.

To illustrate the criteria, Table. 6.1 provides examples of conversations that match the criteria for each learning task. Two quantitative indicators for quantifying the monitoring practice are proposed as follows:

1. **The ratio of monitoring conversations over the total number of group visits:** This indicator measures the extent to which teachers' visits to groups were intended to monitor their mathematical thinking rather than other aspects such as logistics or discipline. Higher values of the indicator for a session indicate relatively more mathematical conversations between teacher and students.
2. **The ratio of probing mathematical conversations to instruction ones:** According to the definition of monitoring (Stein et al., 2008), teachers are encouraged to probe students' thinking rather than give them instructions. This indicator measures the degree in which teachers use probing in their conversations with students.

   To calculate this indicator, each monitoring conversation was first categorized as a conversation to probe students' thinking or provide instructions or both, according to the following conditions.

   – **Probing** If during the conversation, teachers ask students reflective questions on how to perform one or more of the learning tasks or if teachers motivate students to think about a better way to perform one or more of the learning tasks, e.g. *what do you think will happen if we move the robots together?*
   – **Instruction** If during the conversation, teachers directly ask students to perform one of the learning tasks.
   – **Probing-Instruction** If a conversation includes sub-conversations related to both probing and instruction, according to the above-mentioned criteria (the order does not matter).

   Table. 6.1 provides examples of conversations that are defined as probing, instruction and probing-instruction in each learning task.

- **Selecting:** The goal of selecting is to share a group's solution with the rest of the class. Therefore, as a criteria, if teachers talk about a group's solution publicly, it is considered selecting. To qualify it, the purpose of selecting is noted, which could be explicitly stated by the teacher or inferred by their conversations with the students. According to the definition (Stein et al., 2008), the ideal purpose of selecting should be to emerge mathematical ideas.

- **Sequencing:** Students' solutions should be purposefully sequenced with a rationale to connect them with each other. Therefore, as a criteria, if teachers sequence the public sharing of groups' solutions, following a rationale to move from one solution to another, I label it as sequencing. The rationale could be explicitly stated by the teacher or inferred

Table 6.1: Reference for the data analysis explained in Section 6.2. Samples of conversations considered as instances of the monitoring practice of the framework of Stein et al., 2008 with respect to each learning task and whether they are probing students' thinking or are in the form of an instruction or both.

Related Learning task	**Probing /Instruction**	**Example conversation**
Moving robots at the same time	Probing	- Teacher: *Do you think you should move [your robots] separately or simultaneously. Where do you think each robot should move? If you move the robots simultaneously, what do you think will happen?*
	Instruction	- Teacher: *So remember, the aim here is to move both of your robots at the same time. If I move both of them at the same time, it draws a line y equals x. Because when I've got (0,0) Then I've got (2,2), (3,3), (4,4) and so on.*
	Probing-instruction	- Teacher: *Next challenge is to make your line the best. How can you make it better? I think you were not moving your robots simultaneously. How do you think you should move them?*
The relative speed of robots and line slope	Probing	-Teacher: *How do you think you could have made that better? Who was going too quickly?*
	Instruction	-Teacher: *You didn't start at the right spot. You need to start at five and your friend needs to start at zero. And lets go! You're going faster than your friend. But that's the idea. To say you went faster than her.*
	Probing-instruction	-Teacher: *How are you going to guess the line? Ok I give you a hint: You're going to need to know the initial position and then start moving and draw.*
Moving robots along the axes	Probing	-Teacher: *Try to make the green line. Remember which robot goes where? Move them and see what happens. How do you think you can make that line? What's your strategy?*
	Instruction	-Teacher: *I'm gonna give you some advice. You want to move your robots along the axes, so one along the red line and one along the blue line.*
	Probing-instruction	-Teacher: *How are we doing group four? Do you know what you are doing? So can you show me drawing this line? So remember one goes along the blue axis and one goes along the red one. But you want to go by the green line.*
Recognizing the roles of robots in X and Y axes	Probing	-Teacher: *What are your instructions? So what direction is the red one going in? what kind of instructions can you tell them?*
	Instruction	-Teacher: *I love that!! So the second number is the Y axis. I want you to tell them by using X and Y. Which one they start with. Where do they need to end?*
	Probing-instruction	-Teacher: *Where is the Y axis? which one is the X axis? Remember you set the X axis as the one lying down the floor. So, the guider says go to negative three on X axis. Where do you see negative three? Okay, put it there and let's start. Okay?*

by their conversations with the students or the order in which they display selected solutions.

- **Connecting:** The teacher should help students make connections between students' experiences with the activity and the underlying mathematical goals. In line with the definition of the connecting practice (Stein et al., 2008), I assume that a conversation related to the connecting practice should involve *both* words related to the *robot-mediated activity* and the *learning goals*. Thus, I performed a two-step evaluation:

  1. I created two pools of words that could be used by teachers, one related to the students' solutions in the robot-mediated activity and one related to the learning goals. These words were selected according to the definition of the learning activity an it's objective, mentioned in Section 5.1.

     The activity-related words are: red (X) or blue (Y) axes, robot, Cellulo, line, drawing, graphs, movement, map coordination, tablet, activity, teamwork, communication, cooperation; the learning goal-related words are: math, slope, intercept, gradient, X or Y axes, rate of change or its equivalent in curriculum (e.g. rise over run, time over distance), speed, fast(er), slow(er), steeper, equation, start point, end point, straight, horizontal, vertical, perpendicular, diagonal, parallel. Some words were shared between the two pools, e.g. *line*. In that case, depending on the context, the word would be categorized as belonging to one or the other pool, e.g. if the line refers to the one that students draw with their robots, it is considered as an activity-related word, while if the word line refers to the abstract concept of lines, it is a learning goal-related word. I manually filtered interactions into conversations that included at least one word from each pool.
  2. To make sure the appearance of words from the two above-mentioned pools in the conversation was not random, I verified each conversation manually.

  To qualify the connecting practice in a session, I propose the following three indicators:

  – **Number of conversational turns:** Conversational turn is an important unit in studies related to classroom discourse analysis, since researchers propose quantity and quality-related measures, based on it, that can characterise class discourse (Smart and Marshall, 2013; Walsh, 2006). Inspired by it's definition in literature (McHoul, 1978), each conversational turn represents a turn in conversation between teacher and student or between students, i.e. a conversational turn happens when the discourse is transferred from a person to another, e.g. from a teacher to a student and vice versa or from a student to an other. Under this definition, lower values of this indicator show that the conversation is less built on students' participation and that the conversation is dominated by one person (most probably the teacher since they orchestrate the conversations).

  – **Ratio of activity-related words said by students to the ones said by teachers:** Not only it is important that a connecting conversation includes activity-related words and is built on students' participation, but according to the definition of the connecting practice (Stein et al., 2008), students should also be involved in rich conversations about their experience during the learning activity, which is measured by this indicator. Higher values of this ratio indicate that students were more involved in the conversation by talking about their experiences on the activity.

– **Ratio of learning goal-related words said by students to the ones said by teachers:** Similar to the above indicator related to activity-related words, higher values of this indicator suggest that students were more involved in the conversation by talking about the learning goals.

6.3 Results

6.3.1 Overall findings related to OPMD practices

In this section, I firstly explore how teachers in my studies orchestrated the sessions, beginning with the monitoring practice. Table. 6.2 shows the number of episodes of monitoring teachers did for each learning task, per session. Figure. 6.1 (right) illustrates the distribution of monitoring episodes over the learning tasks. I observe that most of teachers' monitoring has been attempts to help groups recognize the role of the robots moving over X and Y axes. Among the other three tasks related to the student-robot-interaction, teachers gave priority to helping student understand the importance of moving the robots at the same time.

Table. 6.3 shows the quantitative indicators for the monitoring practice in each session and Figure. 6.1 (left) illustrates the distribution over these indicators. I observe that less than half of the teacher-group conversations were devoted to monitoring the mathematical thinking of students. Among the conversations related to mathematical thinking, both instruction and probing behaviours are observed. However, individual teachers may have a dominant behaviour; for example, while Albert was giving more instruction, Brian was mostly probing students' thinking.

Related to other practices of OPMD, Figure. 6.2 shows the distribution of selecting and sequencing practices over the timeline of each session, along with the purpose for selecting. In general, teachers attempted to select students' solutions, except Albert and Caroline in her second session. As seen in this Figure, most of the selecting attempts were done using the product bar in CelloRoom 2.0 during both exploration and discussion phases. Four types of rationales for selecting can be identified:

- **To demonstrate good solutions:** This approach, which was always performed using CelloRoom 2.0, mostly happened during the exploration phase (see Figure. 6.2). This type of selection initiates when teachers would observe a group's solution that is outstanding compared to the rest of the class; then they would go to the beamer where the

Table 6.2: Distribution of teachers' monitoring conversations over the various learning tasks (The data for session 7 was not available for analysis)

	Duration (min)	***Teacher***	***Moving robots at the same time***	***The relative speed of robots and line slope***	***Moving robots along the axes***	***Recognizing the roles of robots in X and Y axes***
Session 1	68	Albert	10	8	4	3
Session 2	53.5	Brian	3	0	0	6
Session 3	46.5	Caroline	5	1	10	4
Session 4	44	Caroline	4	5	0	2
Session 5	74	Diana	1	4	2	9
Session 6	48	Diana	1	1	0	7
Session 7	45	Diana	N/A	N/A	N/A	N/A
Session 8	65	Edward	3	2	2	5
Total			27	21	18	36

CelloRoom 2.0 is displayed and search for the group's solution from selection menu on the aggregated mode (Figure. 5.5). The following is an example from one of the Diana's sessions:

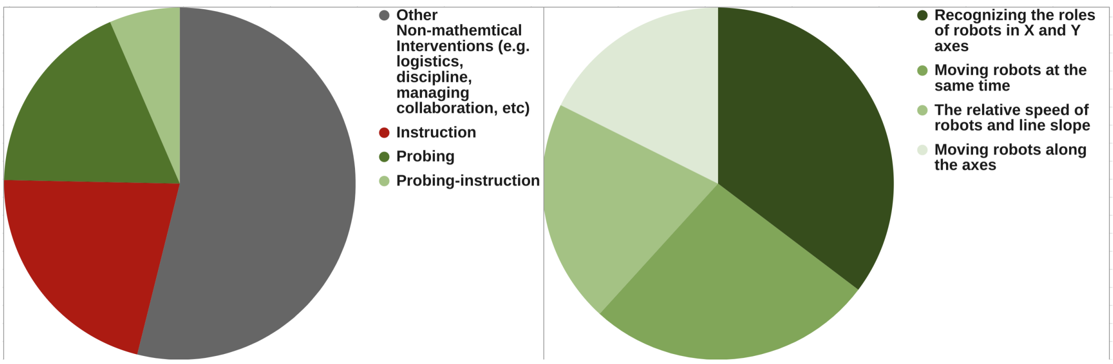


Figure 6.1: Distribution of teachers' monitoring conversations: Left: the ratio of probing to instruction (for all sessions, except sessions 1 and 7) and Right: the proportion of monitoring in each learning task (for all sessions except session 7)

Table 6.3: Detailed information related to the ratio of probing to instruction related to teachers' monitoring conversations (The data for the sessions 1 (only video) and 7 was not available for analysis.)

	Teacher	***Total number of visits with conversation (paying attention silently)***	***Ratio of monitoring/total number of visits***	***Probing***	***Instruction***	***Probing-Instruction***
Session 1	Albert	N/A (N/A)	N/A	2	17	1
Session 2	Brian	21(0)	0.38	6	1	1
Session 3	Caroline	25(2)	0.68	2	10	5
Session 4	Caroline	23(0)	0.35	4	4	0
Session 5	Diana	27(2)	0.66	6	10	2
Session 6	Diana	13(1)	0.6	3	4	1
Session 7	Diana	17(0)	N/A	N/A	N/A	N/A
Session 8	Edward	45(1)	0.26	7	4	1

Diana: *We have had one success without seeing the line on the tablet and it looks like this [referring to the CelloRoom 2.0]: so this [line] is for group three, this is their last effort where they didn't see the line. This is fantastic! Really good job! But what are the words that you're using? They should be the words that a computer needs to hear: very specific instructions. You cannot just say go a little faster, you have to give an idea of how much faster or steeper or whatever words you want to use. And you have to look at the grids. Try and quantify it with a number. Sometimes telling them the beginning and the end point.*

- **To ask students how they draw the lines:** In contrast to the previous selection type, this type would initiate by looking at the product bar on the beamer and later asking a group about their solutions, for example:

Caroline: *Who's group five? Could you give us any tips? What did you do?*
Student 1: *I looked at the robots as well to see the color on the robot, if it's red or yellow. I was telling them to go slower or faster and where they need to finish or where they need to start.*
Caroline: *Brilliant. And where were you moving your robots?*
Student 1: *on the blue [and red] axes.*

- **To reflect on important math concepts** This type of selection was done without using

Table 6.4: The detailed information about the quantitative indicators of connecting practice

	Teacher	***Conversation turns***	***Activity-related words observed***	***Number of activity-related words said by students/ by teacher***	***Learning-related Words observed***	***Number of learning-related words said by students/ by teacher***
Session 1	Albert	4	Robot, movement, coordination	1/7	Faster, slower	1/6
Session 2	Brian	36	Robot, movement, draw, line, spaceship, together, separate, coordinate, line, activity, red, X, blue, Y, separated	25/30	Diagonal, straight, vertical, horizontal, perpendicular, slope, faster, line, X, Y, coordinates	10/25
Session 3	Caroline	4	Graphs, drawing, robots, red, blue, line, moving	3/11	Same or different speeds, line, slope, angle, slower, faster, finish and start points, line	4/6
Session 4	Caroline	27	Graphs, robot, line, movement, blue, red	1/13	Straight, equation (y equals mx plus c), gradient intercept, line, speed, starting point, Y axis, graph	13/23
Session 5	Diana	10	Map	0/2	Slope, start/end co-ordinates, equation (rise over run), speed, faster, steeper, gradi-ent, straight, line	3/24
Session 6	Diana	6	Activity, teamwork, communication, line	3/1	Speed, start and finish point, steeper, faster	6/1
Session 7	Diana	31	Cooperation, com-munication,	2/4	Math, Speed, start-ing position, time over distance, rate, slow, fast, straight, , graphs, x axis, y axis, time over distance	14/16
Session 8	Edward	0		0		0

CelloRoom 2.0, and only by Diana, when she was asking sequentially her students about two or three important words they used to communicate with each other during the activities, that she would then summarize on the whiteboard, as shown in Figure. 6.3, left.

- **To motivate students to perform better:** While in all the above-mentioned types, normally teachers would admire a group solution, in another type of selecting, teachers would ask students to perform better by showing a bad solution or comparing a bad and good solution. Here is an example from Edward:

  Edward: *So about group three, I guess you need to draw the line where it is really need to be, but that's what is recorded! I want you to draw a line like this but you recorded this. Can you improve the line? Should you move the robots simultaneously? Should you move it one by one? How would you move it?*

According to Figure. 6.2, sequencing happened almost in all sessions, except in sessions 1 and 4, and by all teachers, except Albert. The rationale for sequencing (with and without using CelloRoom 2.0) was mostly going over all groups, except Caroline, who sequenced two groups to compare their progress and used this as a motivation to invite her students to think more about guiding each other. The following conversation is an example:

Diana: *Group number one, can you please tell me the three most important pieces of information that you thought was important to share?*
Student 1: *The starting place, distance, like how many steps?*
Diana: *Steps? Okay*
Student 1: *And time*
Diana: *And time. Okay! interesting. Group number two, what did you come up with?*
Student 2:*Speed, also starting position.*
Diana: *What else is your third thing?*
Student 2: *The coordinates.*
Diana: *Very nice. group number three?*
Student 3: *Good communication.*
Diana: *What else?*
Student 3: *Speed and time.*
Diana: *Okay. How did you explain time?*
S: *[Not clear.]*
Diana: *Okay, so does this link to the speed? And so when you're saying timing, which one goes faster and which one goes slower. Do you remember what those two directions are called in mathematics?*
S: *X and Y axes.*
Diana: *In the X and Y axes, you were explaining them. Excellent. And I'm at this table here, group number four?*
Student 4: *So we think that the positions like the starting position and the end position.*

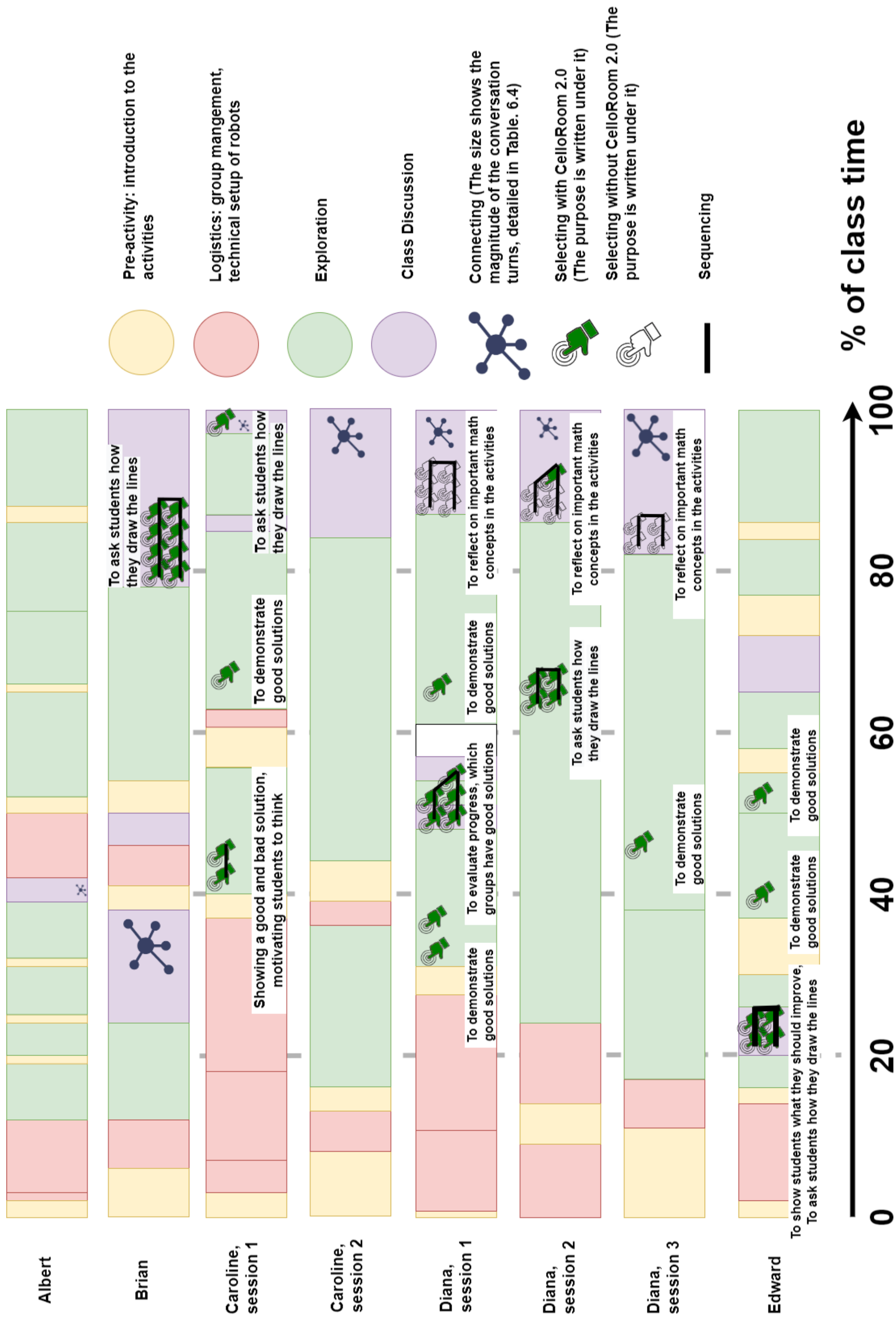


Figure 6.2: The timelines of teachers' actions in their sessions highlights the selecting, sequencing and connecting practices.

In almost all discussions orchestrated by Caroline and Diana (at the end or in the middle of the sessions), the teachers' goal was to connect the robot-mediated activities to the learning goal. In this way, Brian wrote down the learning goals of the activities as a reference for conversations, as shown in Figure. 6.3. Table. 6.4 compares the number of conversational turns among sessions, which ranges from zero to 36 turns, although most of the sessions had ten or fewer conversational turns, with the exception of Brian, Caroline (session 4) and Diana (session 7). Regarding the students' participation in creating rich conversation, even though in some sessions (2 and 7) students' contribution of the activity and learning-goal related words is close to teachers; in general, the majority of these words are contributed by teachers. The following conversation is part of a connecting moment, orchestrated by Brian:

Brian: *Was the coordination of robots difficult?*
Student 1: *I found it difficult because it starts moving like this and separated and I was confused why there is only one spaceship. And then after I figured it out, it became easier.*
Brian: *Now, What did you guys notice about all those lines?*
Student 2: *They were diagonal.*
Student 3: *Horizontal.*
Student 4: *We had a straight line.*
Brian: *So you had a line going like this, right? Did you have any line in between? you had like, X and then Y, but did you have any between x and y?*
Class: *Yes, yes and diagonal*
Brain: *And diagonal. Some lines are vertical, some of them are horizontal. What do you guys call these lines?*
Student 5: *Diagonal*
Student 3: *Perpendicular*
Student 1: *Parallel.*
Brian: *I'm glad you're bringing these types of lines up. For perpendicular always think as the elbow, when you're doing your turn like this?*
Brian: *Okay! We'll come back to the beginning where we talked about the concept of the line slope. It's a line and it's sloping, it slopes up or slopes down. Okay, that's a line slope and you can use what you notice here: there are the coordinates to help you with the line slope.*

6.3.2 Teacher-specific analysis

While the above-mentioned general patterns were observed, each teacher had a specific way of performing practices of OPMD.

Albert

Among the teachers in this study, Albert showed the least engagement in OPMD practices. A possible reason could be that OPMD practices, except monitoring, are performed mainly in the discussion part of the lesson. However Albert had the least amount of discussion time among the participants (as showing in Table. 5.3), which consequently led to less time to be engaged in OPMD practices. According to Tables. 6.3 and 6.2, Albert was monitoring his students in the form of instructions with the focus on the movements of the robots at the same time. In terms of connecting, according to Table. 6.4, Albert had the least amount of conversational turns among all teachers, which occurred in a discussion between the activities (see Table. 6.4 and Figure. 6.2). In this discussion, he merely focused on connecting students works to the learning goals without especially engaging in selecting and sequencing practices, as illustrated in Figure. 6.2. One potential reason for this behaviour could be Albert's preference to use the activities as a consolidation step *after* teaching the concept, as he said: *To me, it was clear what a slope is, and the speed and the link between them. But for them, I think it was all implicit, since I didn't really have a pre teaching moment.*

Brian

In contrast with the session orchestrated by Albert, Brian was very engaged mainly in OPMD practices; according to Tables. 6.3 and 6.2, Brian was asking more questions rather than giving instructions to his students, although with a low ratio of monitoring mathematical thinking w.r.t total visits (less than fifty percent). In the discussion at the end of the class, Brian selected each group's work in each activity (warm-up and first activities) to be shared with the whole class in the sequence of going from the first group to the last one. Although he had the discussion at the end of the class, he pursued to have connecting conversations between the activities with quite high ratio of students' participation, especially with activity-related words.

Caroline

As Caroline performed two sessions, it's interesting to look at the pattern change between the first and second one. In this regard, both increases and decreases in the OPMD practices can be observed. The first thing that we notice by looking at Table. 6.4 is the significant increase in indicators relating to the quality of the connecting practice, including the number of conversational turns. This aligns with the shift from instruction to probing (according to Table. 6.3) in her monitoring practice. One possible reason for this shift comes back to the difference between the percentage of class time she devoted to discussion in the two sessions (4.5% in session 3 and 16% in session 4, according to Table. 5.3). As in the case of Albert, less discussion time led to lower quality connecting practices. At the same time, she did not engage in selecting and sequencing in the second session which is different from her orchestration in the first session (see Figure. 6.2). One possible reason could be that Caroline performed all her selecting in the first session with CelloRoom 2.0. This fact together with her feedback about the difficulty of associating the groups' solutions with their location in class (discussed in Section 5.4.4), could have been a reason to dis-motivate her from continuing the selecting practice.

Diana

Even though Diana had sessions with students of different ages and grades (see Table. 5.1), she kept quite same performance in OPMD. According to Table. 6.2, Diana was paying more attention to how students recognize the role of robots in the activity, keeping the same ratio of probing to instruction and ratio of monitoring per total visits in all the three sessions. While she kept her strategy of selecting and sequencing students' solutions at the end of the sessions, and connecting by asking students sequentially about two important words they used in the activities, she reduced her attempts for selecting and sequencing with CelloRoom 2.0 over sessions (see Figure. 6.2). A potential reason for this could be the difficulty to interact with the interface, as explained in Section 5.4.4.

Edward

Edward was engaged in monitoring (with the highest number of probing instances in monitoring (see Table. 6.3)) and he used the product bar for selecting and sequencing students' solutions with CelloRoom 2.0, mostly at the beginning of the session, to motivate students to perform better. However, he did not attempt to perform any connecting practice, as shown in Table. 6.4. A possible reason for this rather than shortage of time (he had more than an hour, according to Table. 6.2), could be his teaching goal being only letting students explore the activities, as he said: *I was happy because I saw their engagement and that was more than enough! They did different activities and that explains a lot. They were trying to find the easiest way to manage the task and that's good. They manage to do the activities. That shows conceptual understanding. Right! So the main objective was met and that's the most important thing for me.*

6.4 Discussion

The goal of this chapter is to evaluate OPMD practices (Stein et al., 2008) in the context of robot-mediated classrooms and explore teachers' challenges and needs that can be supported by orchestration tools. To facilitate the evaluation process, I proposed quantitative indicators for each practice, which are detailed in Tables. 6.3 and 6.4 and Figure. 6.2. According to the results, there are two opposite cases: while Brian's session shows a high ratio of probing to instruction in monitoring, a high number of selecting and connecting events with a high number of conversational turns and students' contributions in emerging activity and learning-goal related words, Albert showed very low scores in the same measures. The other teachers displayed a different approaches to performing OPMD practices, i.e. performing some practices while not being engaged in others. As an example, Edward selected and sequenced students' solutions, but did not connect the learning activities to their learning goals. This observation, on its own, cannot be concluded as a problem in teachers' OPMD practices. In fact, according to literature, this approach is called *rapid but partial* OPMD and has been observed in similar studies (Choy and Dindyal, 2018). Another example of rapid but partial

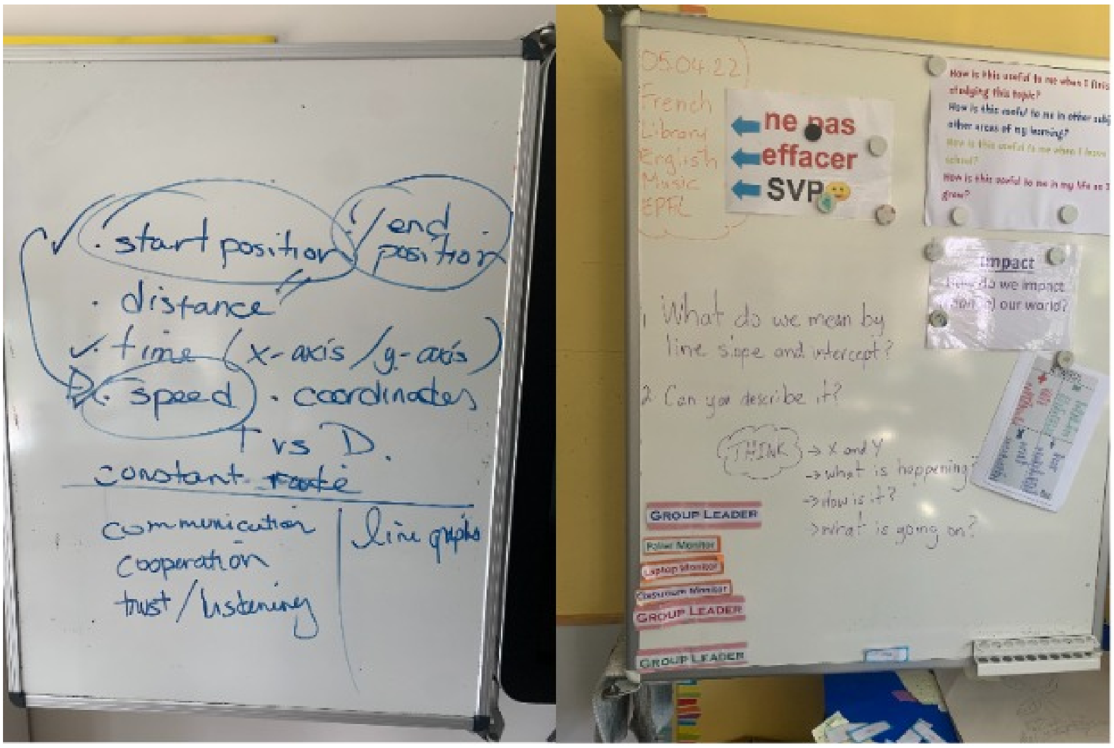


Figure 6.3: Whiteboards of two teachers in the study (Diana (on left) and Brian (on right)) used by teachers orchestrating math discussion in connecting phase. Left: Diana wrote down the most important words coming out from students' reflection on this activity Right: Brian wrote down the learning goals of the activities as a reference for conversations.

OPMD in my study is the case of Albert, who directly jumped to connecting practice without selecting and sequencing before (see Figure. 6.2).

I argue that the diversity in the observed teachers' ways of OPMD roots itself in the differences in real-time class dynamic factors, e.g. how much time the teacher has left for discussion in the session. These differences can result in changes of a teacher's OPMD practice on the fly and as a result one teacher's OPMD can be greatly different from one session to another. For instance, while both sessions 3 and 4 have been orchestrated by Caroline, there is a large difference in students' participation between these sessions with more conversational turns and students' participation in the second one (see Table. 6.4). However, if we look at Figure. 6.2, at the beginning of the session 3, a large part of the session was devoted to technical issues and setting up the activities, which could be a reason for less discussion time and consequently fewer conversational turns in this session. Extending this example, the partial OPMD can be explained by other factors rather than teachers' engagement in performing these practices. We should however not underestimate the role that orchestration tools can play in supporting teachers in improving their orchestration, and therefore I argue that there are still three main teachers' needs, extracted from my results, that if addressed, could potentially enhance the OPMD.

6.4.1 Teachers' Needs to be Supported for OPMD

- **The need for awareness of students' activity data, both related to student-robot interaction and verbal interaction among groups:** According to Figure. 6.1, teachers' attempts at monitoring are both related to student robot interaction and the verbal communication inside each group. Considering the final goal of OPMD, to connect the learning activity to its learning goal (Stein et al., 2008), teachers need to be aware of what happened in the activities in both aspects. As an example, at the end of each session, Diana was asking her students to share two important words that were communicated within groups when performing the activities (which happens verbally).

- **The need for support in purposefully selecting and sequencing:** For these practices, the results show that teachers mostly prefer to choose groups (with or without CelloRoom 2.0) with high performance, probably to increase students' motivation. Although this approach can be beneficial for students' engagement (Do-Lenh et al., 2012), according to the framework of Stein et al. (Stein et al., 2008) the selection and sequencing should be done to *emerge mathematics ideas* rather than to motivate students.

- **The need to reflect on teachers' OPMD:** I argue that for teachers to be able to integrate OPMD practices in their routine, there is a need for them to reflect on their progress over time, as OPMD takes time and practice to develop (Stein et al., 2008). This argument aligns with an effective teacher-training approach which envisions to have reflection sessions with teachers to decide about the necessary changes for improving their teaching (Sluijsmans et al., 2002). This approach could also be helpful for researchers to better understand reasons behind the pitfalls of OPMD in authentic sessions; for example, an observed drawback in my study is that in some sessions (sessions 8 and 1) very few connecting events were observed (see Table. 6.4), however the reason behind this is not clear. With teachers having reflected on this information, it would be clear if this is something they would like to improve in the next sessions or whether they have a special reasoning for continuing this behaviour.

6.4.2 The Possible Role of Orchestration Tools in supporting teachers in OPMD

To address the afore-discussed teachers' needs, having the students' activity data and teachers' conversation with them can play a vital role. It is possible that orchestration tools which are built on these data in real class time, could be helpful to address these needs. I propose the following three functionalities for orchestration tools to answer the three mentioned needs:

- I argue that orchestration tools for OPMD should provide multi-modal aggregation of students' activity data related to the underlying learning goal. In the case of CelloRoom 2.0, the product bar was built based on student-robot-interaction data (see Section 5.2). However the results showed the need for considering both verbal and robot-related data. If information about how students guide each other in the activities is integrated in designing orchestration tools, e.g. by showing the most important words used to communicate in each group, it could potentially lead to a stronger link between teachers' usage of the orchestration tool and the connecting practice, and finally to improving the quality of OPMD. In general, orchestration tools built for robot-mediated classrooms should not be only focused on robot-related data, but other data traces as well, depending on the activity, e.g. in a programming activity traces of students' codes could be necessary.

- To align teachers' purpose of selecting and sequencing with the one envisioned in Stein et al.'s framework (Stein et al., 2008) goal of emerging mathematical ideas, orchestration tools should be designed to support teachers in choosing the groups' solutions that lead to do so. One possible way is to first study the strategies adopted by teachers to emerge mathematical ideas (from literature and, or observation of good practices) and afterwards designing systems to recommend teachers which groups' solutions to select and the order in which to sequence them. For instance, the orchestration tool could recommend groups' solutions that can be compared with each other, e.g. a group's solution which has been obtained by a majority and is incorrect vs. the correct solution performed by another group (Begolli and Richland, 2016). Another example is to cluster students' solutions, based on similarity to the correct answer (Hayashi et al., 2019), so teachers can order the sequence of sharing from the farthest to the closest solution.

- Orchestration tools could show the quantitative indicators proposed in this chapter to teachers for tracking their progress in OPMD. As mentioned in Chapter 2 of this thesis, teacher-reflective tools are known to make teachers aware of the pitfalls and progress of their teaching (Suresh et al., 2021). Orchestration tools can visualize these indicators related to classroom discourse, and this might encourage teachers to improve their progress in OPMD, e.g. by asking more probing questions when monitoring students' mathematical thinking, by purposefully selecting and sequencing students' solutions to emerge mathematical ideas and by connecting students' activity to its learning goal with a high rate of students' participation.

6.4.3 Limitations

The constraints on available data sources have been a main limitation in this study as the only source for recording teachers' voices has been the microphone worn by teachers. As a result, sometimes hearing students' voices in discussion was not easy and some part of the conversation could have been lost. However as the proposed data analysis mainly focus on teachers' discourse and only consider the number of students' interaction within class discourse and not their contents, this does not affect the results significantly.

As a second limitation, while some particular aspects of the orchestration tool, particularly the product bar, have been envisioned to facilitate class discussion as part of constructivist teaching, the teachers who participated in my studies might not have been trained for constructivist teaching. Therefore, the results of our studies could be not only caused by teachers' usage and perception of the orchestration tool, but also by their familiarity with and competence in constructivist teaching, which is hard to quantify, isolate and control for.

Thirdly, there might be teachers' monitoring practices which I did not recognize in our data set. Monitoring is defined as teachers' attempt at paying attention to students' mathematical thinking which could be performed silently or by having a conversation with groups. According to the available data, I could only consider monitoring practices from teachers' voices and I was not able to say whether a silent visit by paying attention, itself, is monitoring or not, and so for the sake of reliability I chose to discard all such events from my analysis. However, as reported in Table. 6.3, the number of visits that involved only silent paying attention is not very large and so would not greatly impact my findings.

Implications of this chapter:

In this chapter I focused on mixed-method analysis of OPMD in the context of robot-mediated classrooms, based on Stein et al's framework (Stein et al., 2008). I evaluated how teachers performed the four practices of OPMD and based on the results, I extracted teachers' needs that can be supported by orchestration tools. These needs and the relevant orchestration functionality I propose, can be summarized as follows:

- The need to be aware of all aspects of students' actions within the activity which should be addressed by designing orchestration tools based on multi-modal students' activity data.
- The need to support teachers in purposefully selecting and sequencing students' solution which should be addressed by designing recommender orchestration tools capable of suggesting solutions to select and the order of sequencing students' solutions.
- The need for teachers to reflect on their teaching which should be addressed by designing teacher-reflective tools that show quantitative indicators based on class discourse and qualifying OPMD to teachers.

7 Conclusion and Future Works

This thesis aimed to identify teachers' needs in orchestrating robot-mediated classrooms, design tools that can tackle them and evaluate such tools in real classroom contexts. In general, this thesis has two main contributions: 1) The identification of teachers' authentic orchestration practices and their needs in orchestrating robot-mediated classrooms and more specifically in orchestrating productive math discussions; 2) The design of an orchestration tool, called CelloRoom, envisioned to address such needs and support teachers in orchestration. Concretely, the tool is used in the context of a set of mathematical activities with tangible Cellulo robots. CelloRoom was iteratively designed in two phases. In each phase, I evaluated its usage, usability and usefulness for teachers' orchestration. In this final chapter, I first briefly mention the contributions that have been made to the literature and practice of classroom orchestration in this thesis. Then, I describe the limitations of my research and avenues for future research that can be pursued by the research community based on this thesis.

7.1 Summary of contributions

7.1.1 Understanding teachers' practices and needs in orchestrating robot-mediated classrooms via classroom observations

Understating teachers' practices

One of the main contributions of my thesis is the investigation of how teachers orchestrate robot-mediated activities. In Chapters 3,4 and 6, I reported and discussed teachers' orchestration practices in robot-mediated classrooms, based on the findings of an observational study which can be used as a reference for designing other types of learning technologies for this context. In Chapter 3, I specifically used classroom observation as my research methodology as it enabled me to identify challenges as they happen in their natural context, thus taking a different approach w.r.t. many works in the literature that focuses on retrospective data such as out of class survey or interviews (Chevalier et al., 2016a). I firstly put myself in the teachers' shoes by running a preliminary study and I later spent more than twenty hours observing teachers orchestrating authentic classrooms in which children were engaging with robot-mediated learning activities. My aim was to look at the teachers' orchestration patterns from the perspective of Prieto et al.'s orchestration framework (Prieto et al., 2011).

In Chapter 6, I studied how teachers perform the practices for OPMD outlined in Stein et al.'s framework (Stein et al., 2008) and named as monitoring, selecting, sequencing and connecting. An important aspect of classroom orchestration is for class discussions to be productive, which envisions letting students first explore the activities and then make the connection between their experience in the activities and the underlying learning goals, by purposefully sequencing and selecting students' solutions to be shared with the whole class. My main contribution in this context is proposing quantitative indicators to measure how well each OPMD practice is transacted in class time. Specifically, I postulate that a productive math class discussion is well orchestrated when:

- Teachers mostly attempt to monitor students' thinking by probing them to think rather than giving them instructions.
- They select students' solutions to be shared with the rest of the class sequentially.
- They orchestrate connecting conversations with a high number of conversational turns and rich contributions from the students in emerging mathematical and activity-related words.

By analyzing teachers' orchestration practices under the lenses of these indicators, I noticed that the 5 teachers involved in my study perform some practices with high quality and at the same time show less engagement in other ones. For example, a teacher attempted to probe students in monitoring,selected and sequenced sharing students' solutions, however did not orchestrate connecting conversations at all or had ones with low numbers of conversational turns. While some reasons for this type of behaviour come back to real time class dynamics, e.g. whether the teacher has enough time for a class discussion, I argue that better results could be achieved if teachers were better supported in performing these practices and progress over time. These findings could be used as a reference for other TEL classroom contexts in the literature of orchestrating class discussions to find the best ways to support teachers in the orchestration practice.

Finding teachers' needs

An overarching goal of this thesis is to find the challenges and needs of teachers orchestrating robot-mediated classrooms and explore whether they can be can be supported by orchestration tools. As discussed in Chapter 3, two important teachers' challenges were found and addressed in the rest of the thesis:

- **Managing robot failures:** Compared to other TEL classrooms, robot-mediated classroom are considered technically complex; in a typical robot-mediated classroom there are ten to twenty robots, usually connected to nearly as many tablets or PCs. I observed that teachers, who are already fully occupied with their routine class management, are continuously concerned about whether one or more groups might be facing technical problems with their robots. This issue was also mentioned by the three teachers involved in the study in Chapter 3 in the interviews. While a long-term solution is to improve the robustness and usability of Educational Robots (ER), teachers need reliable support in becoming aware of such failures as soon as possible, to hopefully reduce their concerns and minimize the disruption caused by such events.

- **Connecting students' robot-mediated activities to the learning goals of the activities:** While literature provides evidence of the effectiveness of robot-mediated activities for learning in individual and collaborative setting, their effect when implemented at class-level is still uncertain (Mubin et al., 2013). I hypothesize that one of the teachers' challenges emerging at class-level is in making the link between the explored activities and their learning goal. In my observations of teachers' actions in classrooms, I found that they continuously tried to make students reflect on the robot-mediated activities at group or class level (via prompting questions or by having debriefing moments), which was in line with their reported concerns of connecting the learning activities to their learning goals. I specifically found that teachers need support in creating discussion moments which relate to the robot-mediated activities. As an example, I observed that one of the teachers involved in study, described in Chapter 3, would ask her students to record their activity with the robots (by taking pictures or recording videos), so that later on she could use them as prompts to ask students' about their activity. I concluded that teachers need to be supported in creating reflection and more specifically discussion moments in class. To this end, literature especially highlights the role of students' data visualization (Do, 2012; Hatch et al., 2011).

These findings were important for building a rationale to support teachers with orchestration tools. At the same time, they highlight the importance of teacher-centered design of orchestration technologies and the key differences between managing robot-mediated classrooms and other TEL classrooms. Furthermore, the findings on how key practices of teachers' OPMD occur in authentic classrooms, presented in Chapter 6, serve as a basis for discussing teachers' needs for improving on their OPMD practices. To summarize, I emphasize the following needs that could potentially be supported by future orchestration tools designed for the context of robot-mediated classrooms:

- In this thesis I relied on students-robot-interaction data to inform teachers about students' progress. Although the initial results in Chapters 4 and 5 showed the importance of such data for orchestration, the results of chapter 6 show that teachers also pay considerable attention to students' verbal communication when monitoring students' thinking. Thus **teachers need to be aware of students' experiences during the activities in both robot-related and verbal aspects**. To this end, in addition to building upon student-robot-interaction data, classroom orchestration tools should also use other sources of information (e.g. verbal communication) which are important for teachers.

- OPMD is a steady and slow process that requires repetition and for teachers to **reflect on their progress over time**. The above mentioned quantitative criteria to measure OPMD can thus serve as a starting point to address this need, since an orchestration tool could visualize teachers' progress in and via these criteria. I especially emphasized the role of classroom discourse, that can provide information about measures of OPMD practices. Hopefully, the proposed quantitative criteria can help teachers see their progress in OPMD practices over time, which can be extremely beneficial in teacher training.

7.1.2 Improving classroom orchestration practices in the context of robot-mediated classrooms

Evaluating usage, usability and usefulness of an orchestration tool (CelloRoom) in the context of robot-mediated classrooms

The second main contribution of my thesis (put forth in Chapters 4 and 5) is the investigation of how using an orchestration tool, named CelloRoom, could facilitate teachers' classroom orchestration. In this regard, I studied teachers' usage of the tool and their feedback on its usability and usefulness for orchestration. It is clear that only ecological studies in authentic classrooms allow for all aspects of classroom implementation of orchestration technologies to emerge and be properly assessed. The core objective for the design of CelloRoom was to answer the teachers' needs observed in Chapter 3. To retain the emphasis on teachers' needs and their orchestration practices, the design process included two iterative phases (CelloRoom 1.0 described in Chapter 4 and CelloRoom 2.0 described in Chapter 5). CelloRoom included two main functionalities, namely the robot failure alert and an awareness functionality provided in aggregated mode, via the progress bar, or in detailed mode, via the product bar.

1. The robot failure alert (the noticeable red alert on top of CelloRoom) had a positive impact on teachers' actions, ensuring they would *notify* the failure and prioritize visiting groups with failures (in all cases in the second iteration and in most cases in first iteration). Based on the interviews, I can conclude that it reduced teachers' concerns about technical failures, as indeed most teachers in the two iterations of the experiments found it helpful to detect groups with robot failures. This alert is different from other ones in literature (Martinez-Maldonado et al., 2013) in the sense that it also can be notified from students in the classroom, i.e a student might come to the teacher and notify them about a robot failure. There were in fact teachers in our studies who mentioned their preference for only relying on students' feedback rather than using CelloRoom to be notified of robot failures. A surprising observation arising from studies in Chapters

4 and 5 is that even those teachers used CelloRoom to *validate* students' claim of a robot failure. As a conclusion, I emphasize the necessity of testing orchestration tools in class-time to evaluate *all types of possible benefit* that a functionality could have, since an orchestration functionalities (e.g. robot failure alert) could be used differently (for notification and validation) than what envisioned by researchers (only for notification). These results could be potentially extended to other robot-mediated classrooms. While CelloRoom only alerts teachers in case of a failure in Cellulo, in other robot-mediated classrooms, like programming robots or "make your own robot" paradigm (Alimisis et al., 2019), the source of error might be multiplied. For example, in programming classes, the failures may happen in the table-top robot, in the laptop or in the connecting cable and teachers are confused about the source of problem. I argue that the need for a failure alert becomes more important for orchestrating the classes where students make a robot by building its mechanical and electrical parts, since the possible sources of failure become more complex due to students' usage of many tools and components.

2. CelloRoom provided different types of awareness information about students' progress, based on students' interaction with the robots. One functionality, called progress bar, provided quantitative measures of students' progress, i.e. the number of steps they completed in the activity, while another functionality, called product bar, provided information about the students' artefacts in the activity (their scores over time or the lines they drew with Cellulo robots). The progress bar was used only by two out of six teachers involved in study in Chapter 4 for deciding the transition moment to the next activity. In general, teachers preferred the detailed information provided by the product bar over the aggregated data displayed in the progress bar, i.e teachers wanted to know how students performed in an activity rather than just knowing they finished it. Students' artefact data were used to create discussion moments, albeit differently between the two iterations of design; i.e. relying on two different forms of data visualization (textual visualization of the students' scores in CelloRoom 1.0 and graphic visualization of the students' lines in CelloRoom 2.0). Teachers found the graphic visualization an easier way to evaluate the quality of students' solutions. I observed that teachers use the awareness functionalities differently from each other; searching for possible reasons in teachers' interviews, I found that *class dynamics* play an important role in determining the type of usage of orchestration tools; for example students' scores in the robot-mediated activities was used in one class while not in another, because the second teacher wanted to avoid unhealthy competition among students.

Empirically-validated robot-mediated learning activities

A side, but worth-mentioning contribution of my thesis is the design of a series of empirically validated robot-mediated learning activities for teaching two fundamental topics in mathematics (the notions of coordinates system and line slope), one of which obtained positive learning gains at *class-level* from eighty students and for the other one, although learning gains could not be computed, but related teachers' feedback was positive. My goal was to valorize the role of teachers in the design of the robot-mediated learning activities, since supporting teachers is not only achieved by designing effective orchestration tools but also by including their feedback in the design of robot-mediated learning activities. In this approach, the teachers' feedback is included in both learning technologies in the class and orchestration technologies for teaching .

Design guidelines for orchestration tools

Chapter 5 of the thesis provides a comprehensive list of design guidelines for orchestration tools in robot-mediated classrooms. As a conclusion, I would like to emphasize here three important ones:

- **Flexibility in design:** one of the main findings of my thesis regarding teachers' usage of orchestration tools is that a same functionality is often used in different ways and to different purposes by teachers (e.g. according to the real-time class dynamics). Therefore, aligned with Dillenbourg's principles of design (Dillenbourg, 2013), orchestration tools should be designed to support teachers' flexibility in taking orchestration actions; for example concerning controlling the activity sequence, some teachers preferred controlling groups one by one while others preferred to control the activity sequence in a class-level. Thus, it is required that orchestration tools provide multiple options for the same orchestration action.

- **Providing students' progress indicators that show the quality of their works:** as mentioned before, teachers prefer to have information that help them to qualify students' activities rather than merely know whether they have finished an activity. In the study performed in Chapter 5, teachers appreciated graphical data visualizations in orchestration tools, such as graph representation of data, over textual visualizations, like scores (that CelloRoom 1.0 had). I postulate that orchestration tools should visualize the features from the robot-mediated activity such that teachers can understand the envisioned information easily, e.g. by prioritizing providing graphic representations from student-robot-interaction as much as possible.

- **Simplicity in associating the information on the orchestration tool and the students in the class:** It is important that teachers can easily map what they see on the orchestration tool to the physical class and vice versa. For instance, if the orchestration tool informs teachers that a group has a technical problem, they should be able to easily identify which group it is and locate them in the class. Similarly, when teachers find out that a group has a good solution while moving around in the class, they should easily find that solution on the tool and be able to share it with the rest of the class. In CelloRoom 2.0, groups' solutions were associated with the corresponding group number, but teachers had difficulty associating the group numbers on the tool with the students in the class, since there was not a clear association between students' names and the number of the group they belonged to.

The design guidelines for orchestration tools, provided in the thesis, are in many cases aligned with the existing ones in literature and can be extended to other TEL classrooms. For instance, the first guideline about flexibility in design seems directly related to Dillenbourg's principles of design for orchestration (Dillenbourg, 2013) and Rodriguez et al.'s emphasize on the possibility of having multiple solutions for a single teachers' need (Rodrıguez-Triana et al., 2021). The second and third guidelines are more about the way to visualize the students' activity for teachers to make decisions instantly and improve the usability of orchestration tools which I argue that they can be generalized to other TEL classrooms, however being carefully designed according to the context and the underlying learning activities. For example, in the design of the product bar in CelloRoom 2.0 (mentioned in Chapter 5) I showed that the path of the Cellulo robots (or generally speaking students' movement traces on the learning technology) can be used to build a measure on how well students have preformed the activity for teachers. While this measure was found to be useful for teachers in my experiments, the same measure using students' movement traces on the technology might not found to be useful in another learning activity with the same robot or using another technology (e.g. tablet or Virtual reality).

Evaluating the role of orchestration tools in orchestrating productive math discussion in the context of robot-mediated classrooms

This thesis attempted to improve the constructivist culture of robot-mediated classrooms and especially support teachers in *orchestrating productive math discussions (OPMD)* in robot-mediated classrooms. The goal of the work discussed in Chapter 5 was to evaluate the usage of a functionality, called product bar, included in CelloRoom 2.0 and specifically designed for OPMD and assess whether it is useful for supporting teachers in the OPMD practices of selecting, sequencing and connecting. Comparing to the similar work in literature (Do, 2012), I studied teachers' usage of the orchestration tool through the lens of Stein et al's framework (Stein et al., 2008). According to the results, CelloRoom 2.0 was proven to be helpful in the important practice of selecting students' solutions to be shared publicly. Almost all teachers sequenced sharing students' solutions by going over all groups one by one, to guarantee the participation of all students in the class. Teachers mentioned that their main intention for using the tool was to engage students in class discussions and provide a basis to create discussions and ask questions. However, the findings showed that there are two main gaps in the usage of the product bar to the purposes of OPMD: 1) I did not find evidence that the rationale used by teachers for selecting and sequencing students' solutions was related to the goal of raising mathematical ideas, which is the goal of OPMD framework (Stein et al., 2008); 2) the relation between teachers' usage of the product bar and connecting practice was not found to be strong, i.e. only in two out of the eight sessions, the product bar was used when teachers had a connecting conversation with students.

7.2 Limitations

One of the principles guiding the work presented in this thesis was to only consider authentic in-person classrooms for experiments, which is the only way to have a complete and authentic view of teachers' orchestration practices and challenges. Thus it was not easy to find teachers willing to participate in my studies. Since, for the ecological validity of my findings, I wanted teachers to assess the orchestration tool by using it in a real lecture, I had to ask them to use a new teaching method (teaching the topics in mathematics) alongside a new tool (the orchestration tool). This made it challenging for me to motivate teachers to participate in my studies, and specifically more challenging than other approaches followed in the literature which require teachers to only familiarize with the tool. This difficulty in recruiting was the primary reason for the relatively small number of participants in my studies. However, I believe that the rich qualitative analysis of classroom observations in the thesis adequately compensates for this limitation, providing otherwise unattainable insightful findings on teachers' orchestration process. Another difficulty of conducting authentic studies relates to performing pre and post tests to assess the effectiveness of the learning activities: while in a laboratory-settings study, researchers control the session flow and can thus ensure that pre and post tests are performed as necessary, in my study teachers had full control of the sessions, which caused pre and/or post tests to be discarded in some sessions due to lack of time or teachers' desire to rather focus on the activities. Also, I could only consider classrooms in which teachers use CelloRoom while for studying the effects of its usage, there is a need for the baseline in the studies (i.e., having the same teachers orchestrate a robot-mediated classroom without CelloRoom).

Secondly, the focus of the thesis has been limited to real-time in-class teachers' behaviours, while orchestration scope also extends to out of the classroom practices; both orchestration frameworks used in this thesis (Priero's (Prieto et al., 2011) and Stein's (Stein et al., 2008)) also mention the out-of-classroom factors in orchestration (e.g. design/preparation in Prieto's orchestration framework and anticipation in Stein's framework). As a result, this thesis has the limitation of not considering the role of elements outside of the class (e.g. the lesson design, the teachers' planing of the session, etc) that can impact the in-class teachers' orchestration behaviours.

Thirdly, the scope of the robot-mediated activities in this thesis does not cover the whole paradigm of robot-mediated activities in literature. The activities in this thesis have been only limited to teach mathematics with a collaborative script and with a single educational robot (Celullo), while robot-mediated activities have a wide range of topics in other STEM-related topics. like physics, chemistry, programming and importantly in building robots and *make your own robot* paradigm (Alimisis et al., 2019) that could not be covered in this thesis. While whenever possible, I have tried to generalize the results, some results might not be generalized out of the particular learning activities in the thesis.

Fourthly, most of the teachers could use the developed learning system only once (with only two teachers being able to use it for more than one session) while normally it takes more than one session for teachers to adapt to a new teaching technology. Although we tried to provide the best possible training (by performing a realistic practice sessions and providing different kinds of presentations) before the sessions, teachers mentioned forgetting important part of how the activities should run or about how to use the orchestration tools, during their session, which could have thus impacted both their usage and perception of the tool, as well as their classroom orchestration process. This limitation could have affected the teachers' self-confidence and their orchestration practices. Repeating the activities with each teacher multiple times will lead to more reliable and authentic findings concerning teacher practices and the efficacy of orchestration tools designed to support them.

Lastly, the global pandemic due to the virus COVID-19 had severe impact on the process of conducting experiments in 2020-2021. Many schools closed and move to online teaching, and even after re-opening to in-person teaching they did not allow visitors on the school premises. Although I tried to mitigate this limitation by performing part of the iterative design of the learning activities in online settings, as described in Section 4.1.3, this fact brought delays and disruptions to my studies and their scheduling.

7.3 Implications for current and further research

7.3.1 Multiple orchestration tools in classrooms

According to the results of Chapter 4, the teachers' interaction method with the orchestration tool should be mindful of the limited attention they can devote to the tool during class time. Teachers appreciate orchestration tools that take minimum attention when going around the class. With this rationale in mind, some functionalities of CelloRoom, namely the robot failure alert, could be shown on a wearable device, e.g. a smart watch. In this way, the notification of a specific failure event could be given to teachers via vibrations or sonic alerts (Quintana et al., 2016). At the same time, I observed that different devices are better suited for different moments: for example after the activities teachers might want the attention of the whole class to be on the orchestration tool, by projecting students' activities on a beamer, while at other times they might need to display information on their personal computer to have a private space. As conclusion, I found that one device can not support teachers in every class moment.

Indeed, a variety of existing works in literature have investigated pros and cons of various orchestration devices, each intended to be the sole one used in classroom. Explored solutions range from distributed tools on students' desks (Alavi et al., 2009) to smart glasses (Holstein et al., 2017). Although each of these works has explored the usage of one particular device as an orchestration tool, a research gap still remains to explore the usage and usability of multiple devices forming the orchestration tool in the classroom (An et al., 2020). Considering the scenario in which teachers have access to multiple devices in a session, we should investigate whether the presence of multiple devices helps teachers leverage the advantages of each

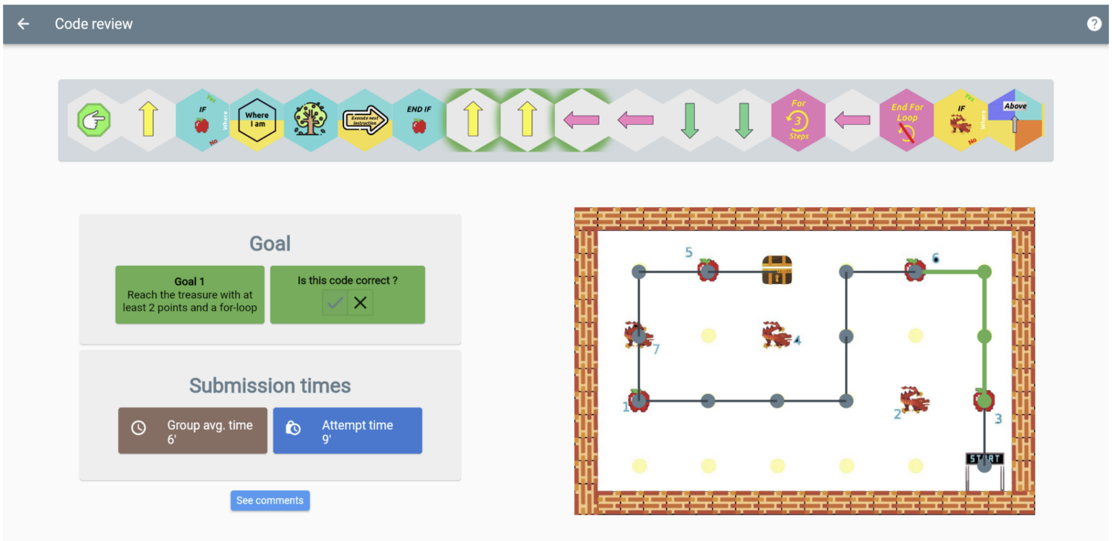


Figure 7.1: A page of an orchestration tool developed for robot-mediated programming activities that can show students' code (at the top, in the format of hexagon blocks) and the behaviour of the robots deploying such code (on the right). This tool can help teachers have an overview of students' actions within a robot-mediated programming activity.

device, or rather multiplies their challenges by having more technologies in classroom.

7.3.2 Extension of the proposed orchestration tool to open-ended project-based robot-mediated classrooms

As mentioned at the beginning of the thesis (Chapter 2), one of the main challenges of designing orchestration tools is their strong dependency on the learning context. This thesis evaluated the usage of orchestration tools in a robot-mediated classroom with the specific learning goal of teaching a topic in mathematics and a single educational robot. However an important part of robot-mediated classrooms in literature focuses on classroom activities aiming to more ope-ended project-based lessons, for example to teach programming (Mubin et al., 2013) and ER paradigm “make your own robot” where learners are doing projects that can take unpredictable paths Alimisis et al., 2019; Jormanainen, 2013. Extending the research methodology proposed in this thesis to a robot-mediated classroom with open-ended project-based context is one of the main research directions for the extension of this thesis. As discussed in Chapter 3, the challenge in this context is for the orchestration tool to effectively summarize robot traces in one glance for teachers. Figure. 7.1 shows the orchestration tool that I contributed to develop and test in the laboratory settings with a teacher and two students. The tool shows the path of the robot and the programming lines provided by students in the form of block-based programming. While the tool was preliminary evaluated in two studies involving more than ten students, Further research is required to evaluate the usability and usefulness of this tool in such sessions.

7.3.3 Automatic classroom discourse analysis for teacher-reflective orchestration tools

The results of Chapter 6 shows the importance of quantitative measures to qualify how teachers orchestrate class discussions to be productive, however extracting these measures manually is a cumbersome process and needs hours of analysis. Beside time, human errors, biases and subjectivity can affect the output of such analyses, thus motivating to move towards and develop automatic analysis and annotation systems. The added value of such systems is that the data can be directly provided to teachers in the orchestration tools. To do so, we need to synthesize the class discourse (in format of a speech), extract the quantitative measures and display them via effective visualization formats in the orchestration tool.

Orchestration tools that provide feedback to teachers about their teaching, based on the classroom discourse, are gaining interest within the research community (Suresh et al., 2019) and are especially found to be useful in teacher training (Chen, 2019; Jensen et al., 2020) and to increase students' participation in class discourse (Z. Wang et al., 2013). The main challenge is the evaluation of these tools in real class time. To address this research gap in literature, a follow-up of this thesis includes evaluating the usage of an orchestration tool providing the above mentioned quantitative measures and its usefulness for enhancing the orchestration of productive math discussions in class time.

7.4 Closing Remarks

This thesis summarizes four years of research with the aim to investigate where teachers need support with orchestrating robot-mediated activities and how this support can be provided by orchestration technologies, which can potentially lead to a better usage of ER for teaching. A significant part of this thesis was devoted to understanding teachers' needs and, as a solution, an orchestration tool called CelloRoom was designed in two iterative phases. The evaluation of CelloRoom in authentic robot-mediated classrooms across Switzerland not only showed the advantages of using it for managing real-time class events, like a robot failure, but also led to proposing novel quantitative measures for qualifying the orchestration of productive math discussions in robot-mediated classrooms to foster math reasoning when students interact with robots; i.e. probing students' mathematical thinking, sharing their solutions to emerge mathematical ideas and connecting between the student-robot-interaction in the activity and the activity's learning goals.

In addition to the scientific findings and contributions that this thesis makes to the literature in *Educational Robotics* and *TEL classroom orchestration*, it is worth to mention the impact that this thesis had on the educational system in the area where studies were conducted (which is the ultimate goal of all the research in this area): more than 10 teachers and 200 students used the orchestration tool and the robot-mediated learning activities developed in the context of this thesis for teaching and learning mathematics. These students, aged 7-14, were given the opportunity to interact with Cellulo robots for the first time. Considering teachers, a key outcome is the successful transition of the research done at university to schools and in their hands. I believe that including teachers in research is the only way to guarantee the success of teaching/learning technologies in schools.

A Pre and post-test for measuring students' learning gain in regards to coordinates system topic

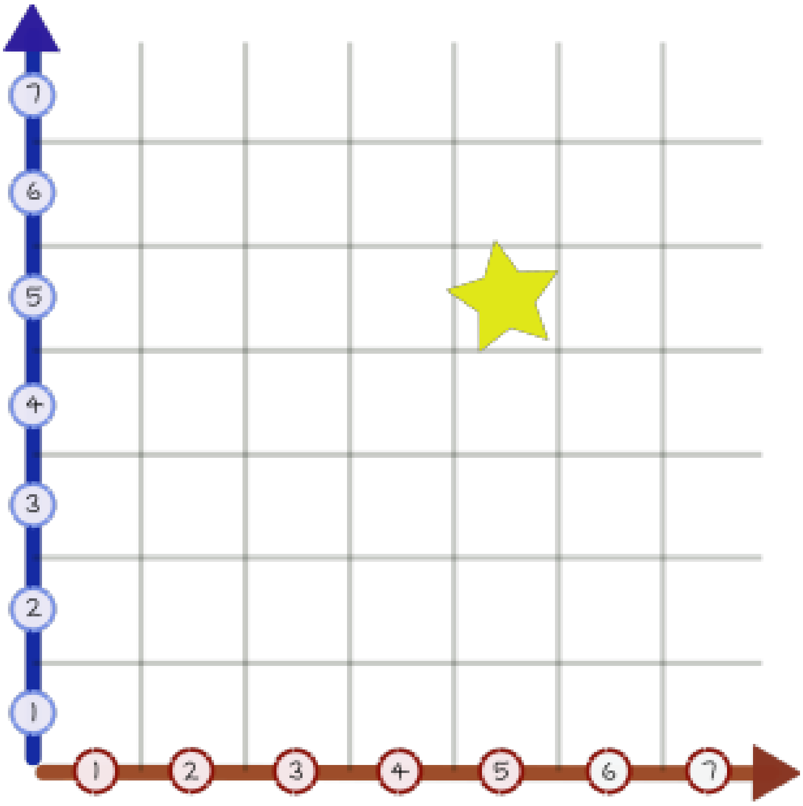
A.1 Pre-test

Your name:

Your group number:

Stars are visible in the images below. Numbers on the horizontal (red) and vertical (blue) axes are available to indicate their position.

1) Choose the answer which indicates the position of the star.

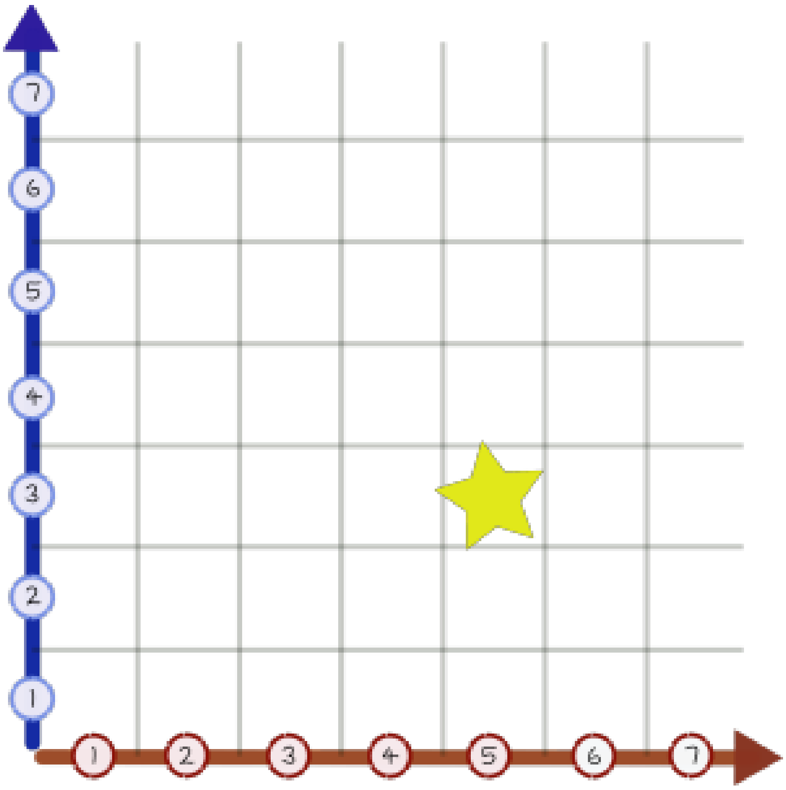


A) Horizontal position (red) of 3 and vertical position (blue) of 4

B) Horizontal position (red) of 3 and vertical position (blue) of 7

C) Horizontal position (red) of 5 and vertical position (blue) of 5

2) Choose the answer which indicates the position of the star.



A) Horizontal position (red) of 5 and vertical position (blue) of 4

B) Horizontal position (red) of 3 and vertical position (blue) of 4

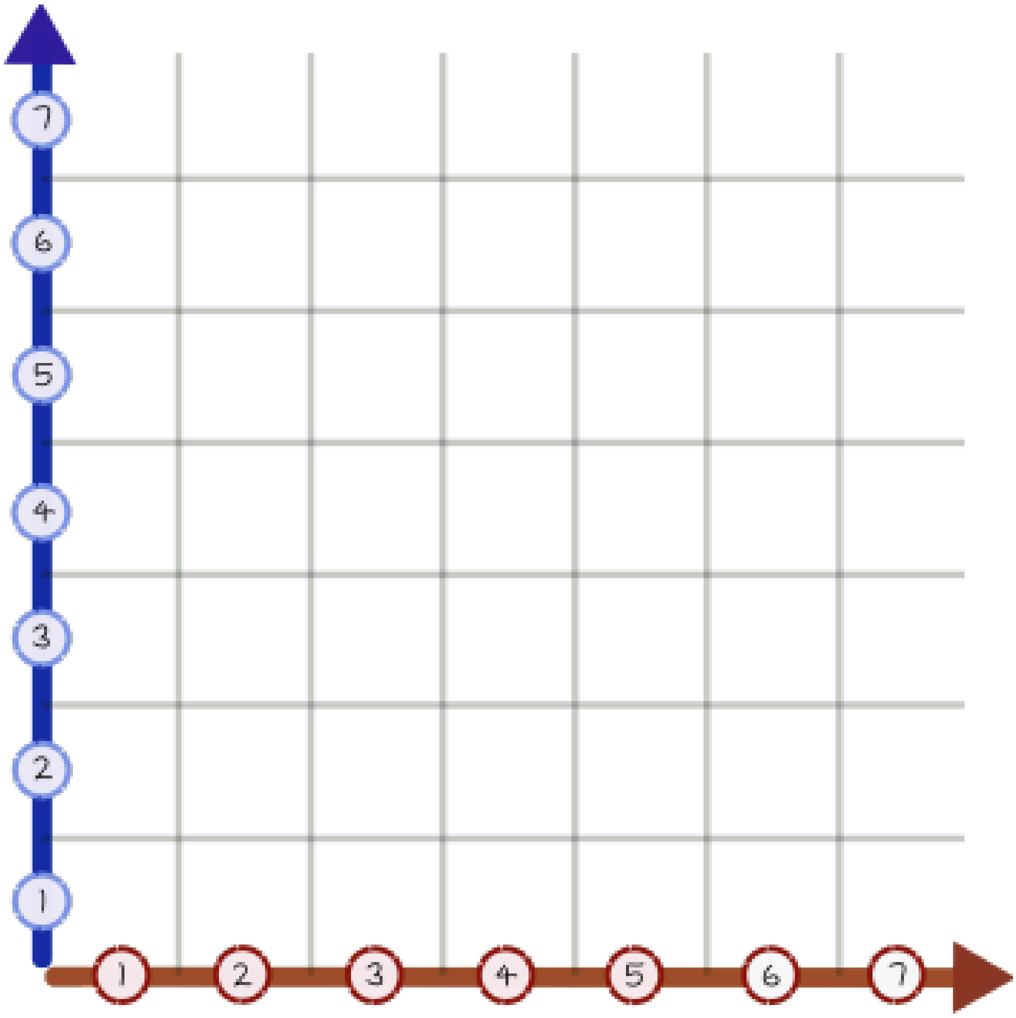
C) Horizontal position (red) of 5 and vertical position (blue) of 3

3) Draw a star at these positions on the map (Grid):

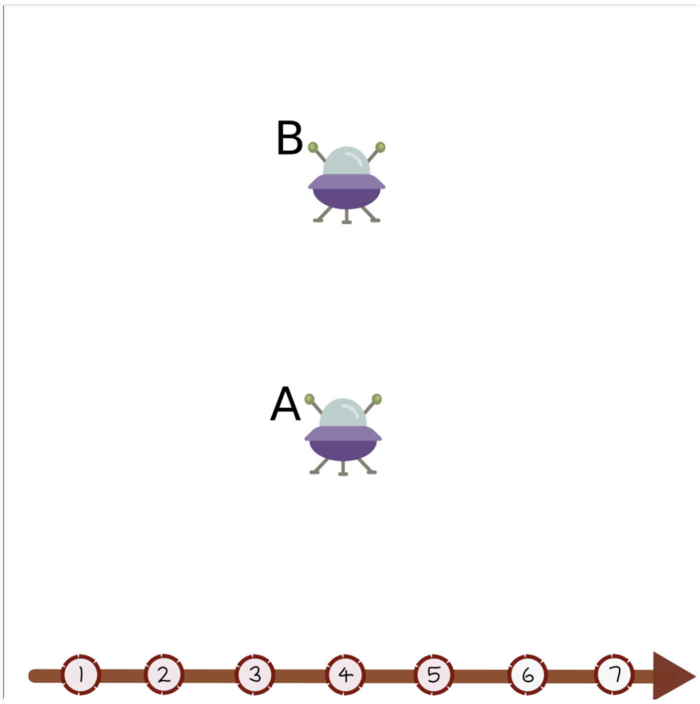
A) Horizontal position of 2 and vertical position of 4 and name it star A.

B) Horizontal position of 2 and vertical position of 7 and name it star B.

C) Horizontal position of 4 and vertical position of 3 and name it star C.



4) How do you describe the position of spaceship A? Does spaceship A have the same position as spaceship B?

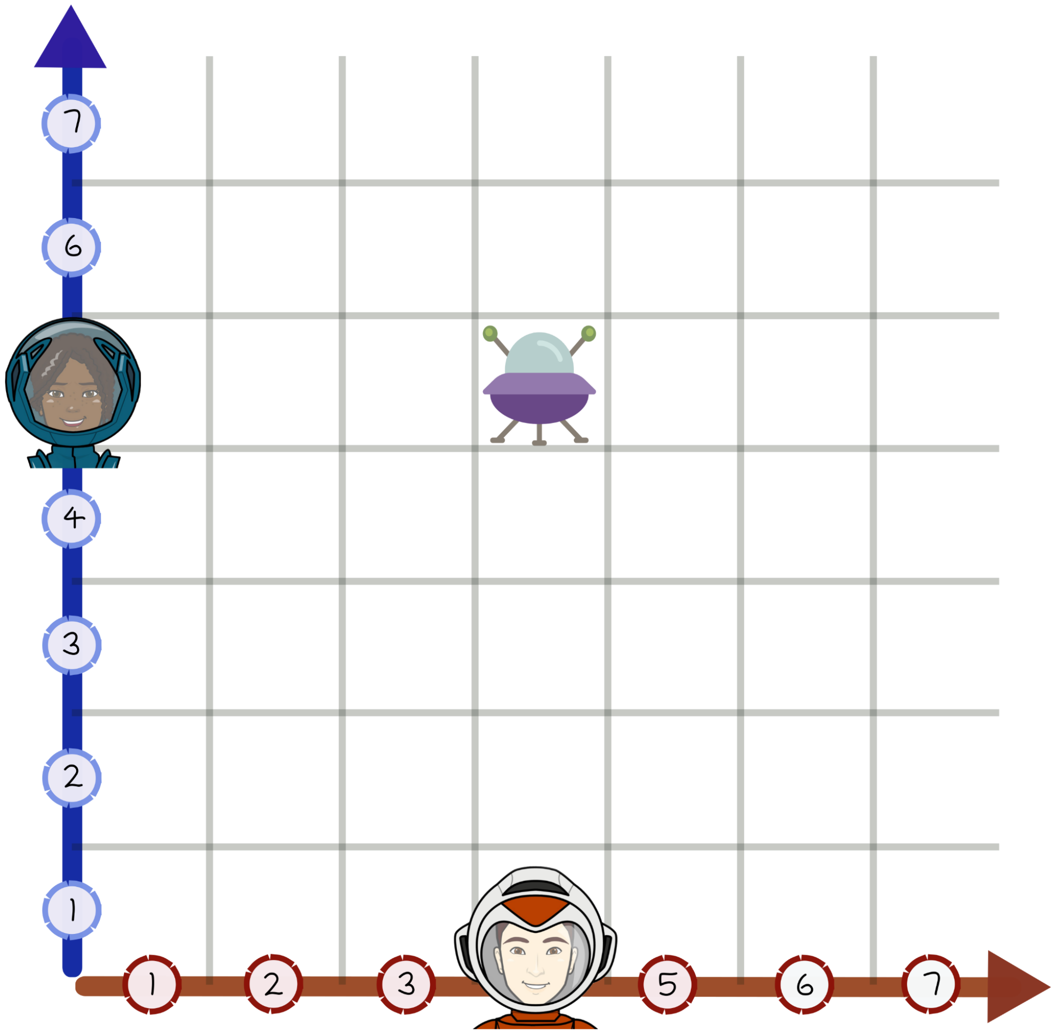


Your answer:

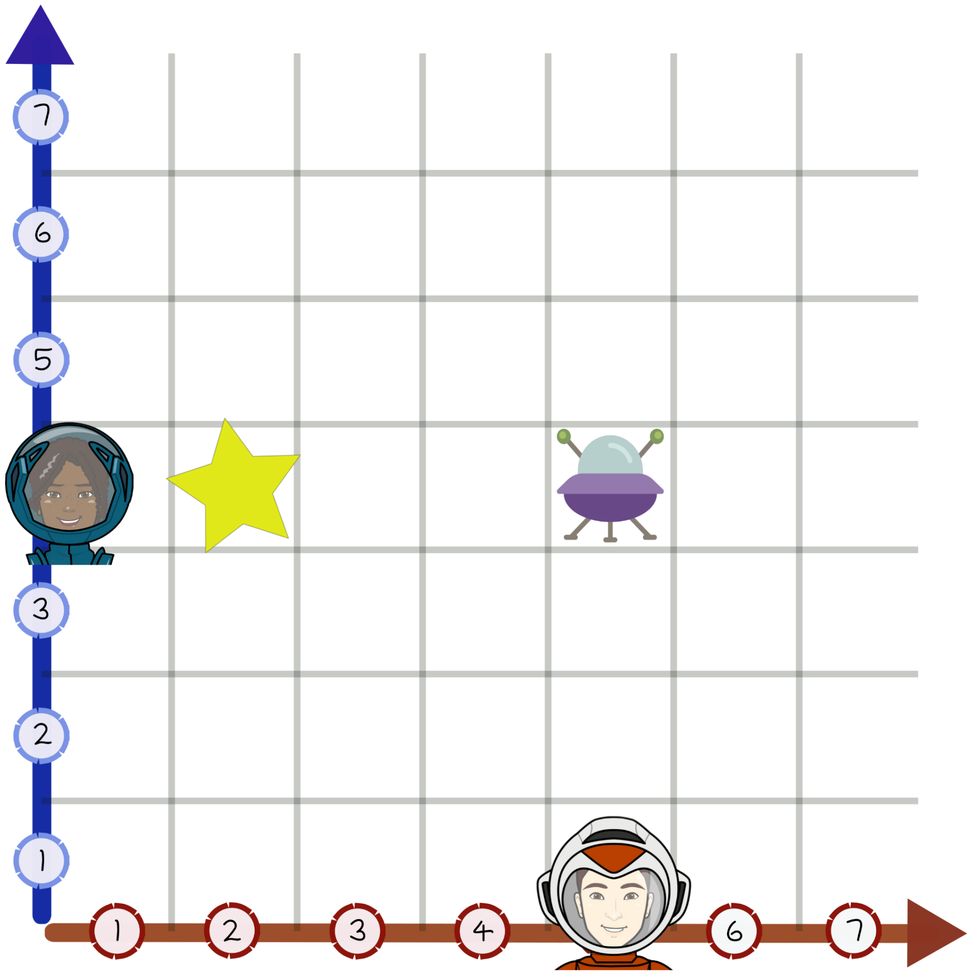
In the pictures below, the red astronaut can only move left or right. The blue astronaut can only move up and down.

If the red astronaut moves left or right, the spaceship will move left or right.

If the blue astronaut moves, the spaceship will move up or down.



5-1) In this picture, report which astronaut must move, so the spaceship can reach the star?

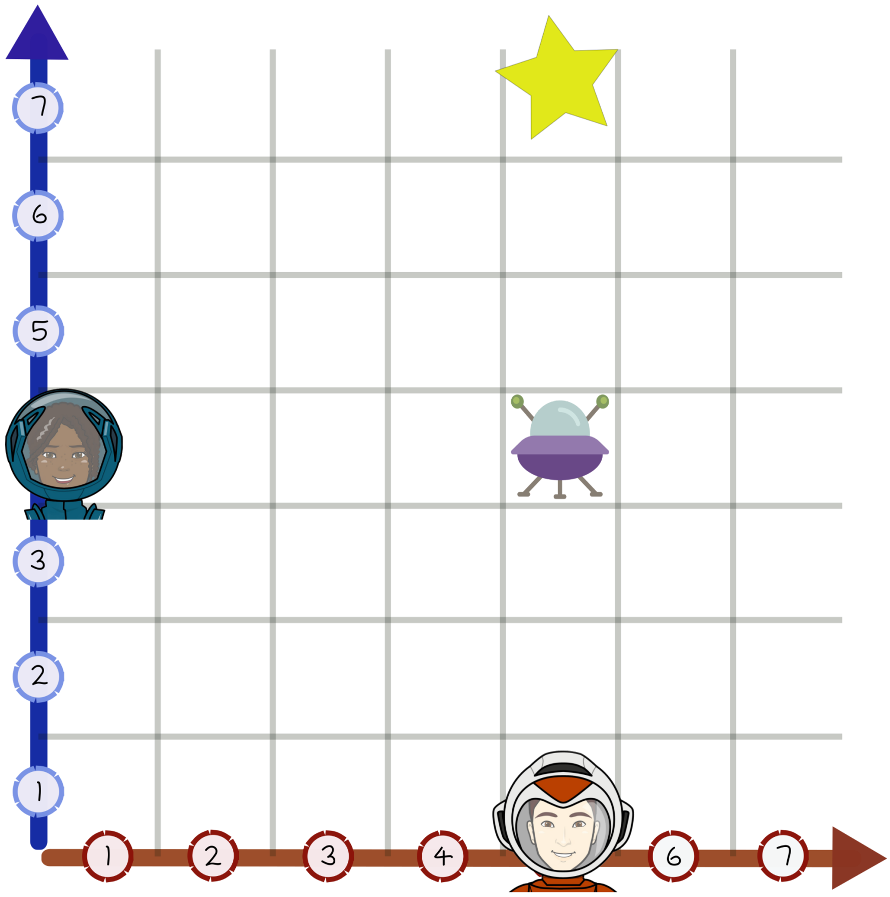


A) Only red astronaut should move

B) Only blue astronaut should move

C) Both astronaut should move

5-2) In this picture, report which astronaut must move, so the spaceship can reach the star?

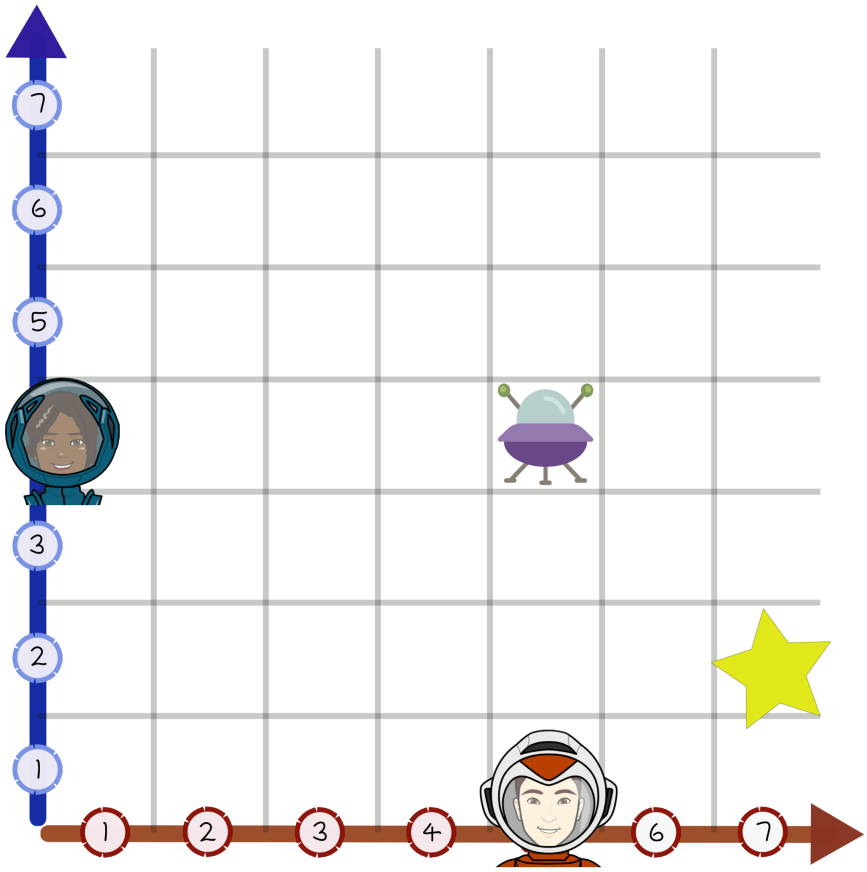


A) Only red astronaut should move

B) Only blue astronaut should move

C) Both astronaut should move

5-3) In this picture, report which astronaut must move, so the spaceship can reach the star?



A) Only red astronaut should move

B) Only blue astronaut should move

D) Both astronauts should move, it doesn't matter who goes first.

E) Both astronauts should move but the blue one should go first.

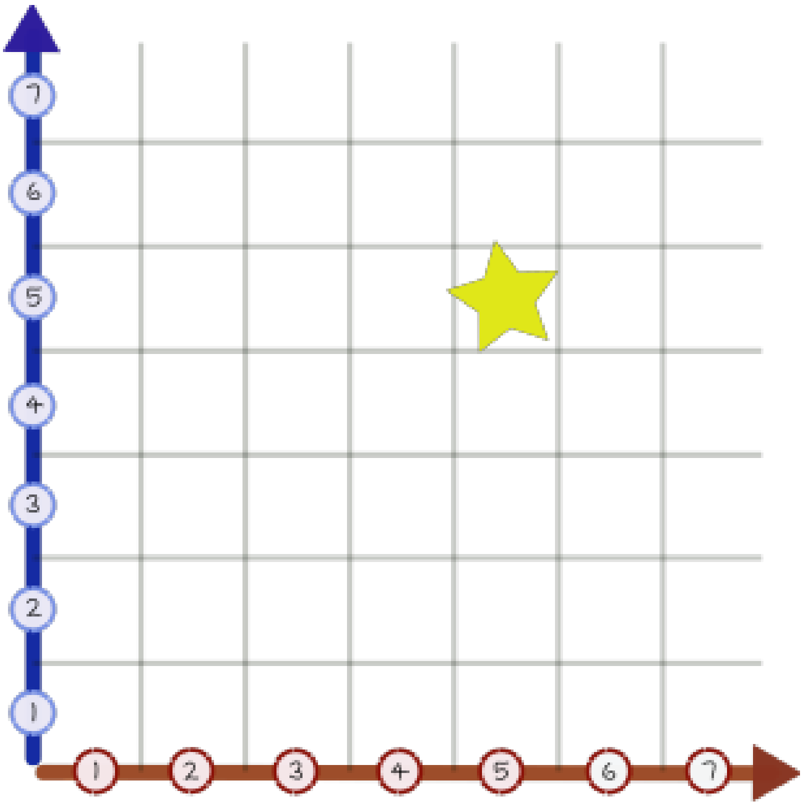
A.2 Post-test

Your name:

Your group number:

Stars are visible in the images below. Numbers on the horizontal (red) and vertical (blue) axes are available to indicate their position.

1) Choose the answer which indicates the position of the star.

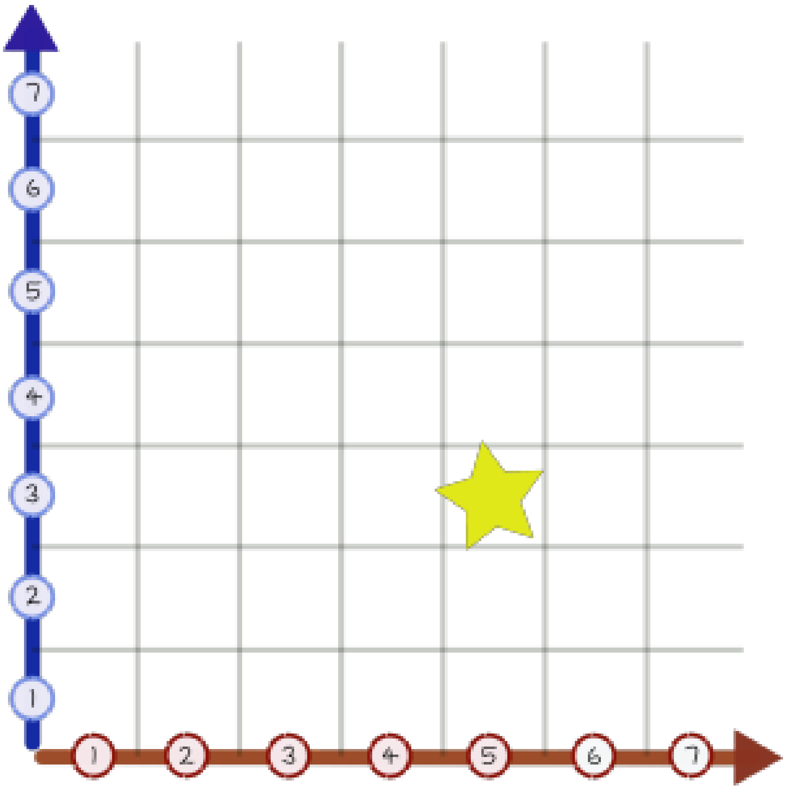


A) Horizontal position (red) of 3 and vertical position (blue) of 4

B) Horizontal position (red) of 3 and vertical position (blue) of 7

C) Horizontal position (red) of 5 and vertical position (blue) of 5

2) Choose the answer which indicates the position of the star.



A) Horizontal position (red) of 5 and vertical position (blue) of 4

B) Horizontal position (red) of 3 and vertical position (blue) of 4

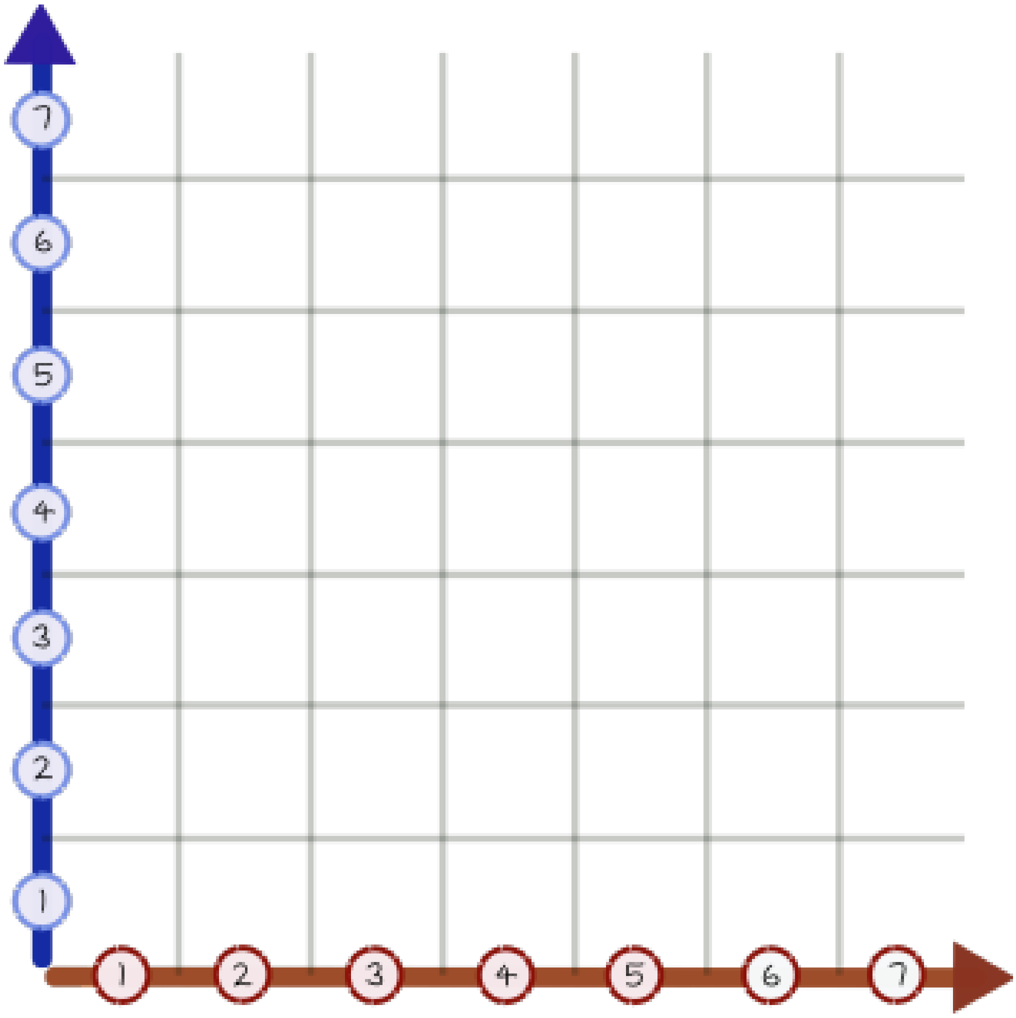
C) Horizontal position (red) of 5 and vertical position (blue) of 3

3) Draw a star at these positions on the radar (Grid):

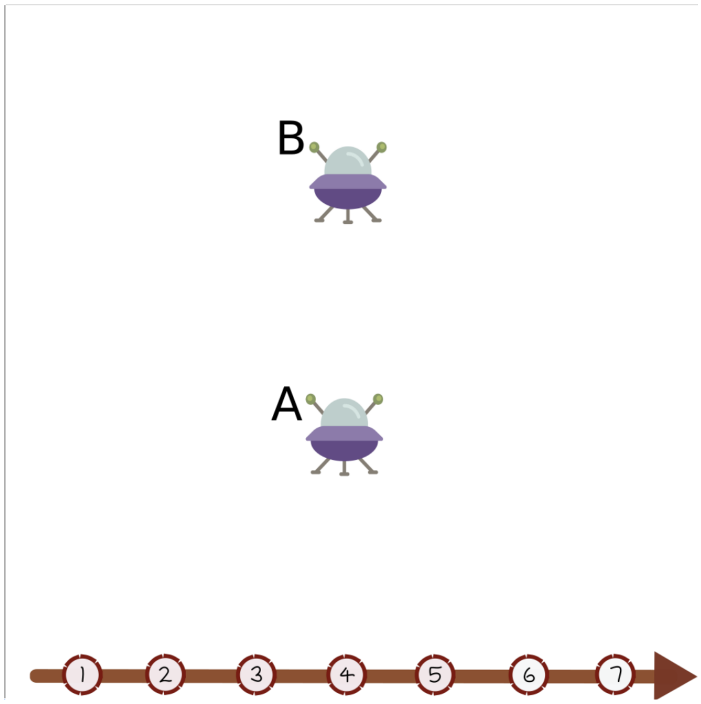
A) Horizontal position of 2 and vertical position of 4 and name it star A.

B) Horizontal position of 2 and vertical position of 7 and name it star B.

C) Horizontal position of 4 and vertical position of 3 and name it star C.



4) How do you describe the position of spaceship A? Does spaceship A have the same position as spaceship B?

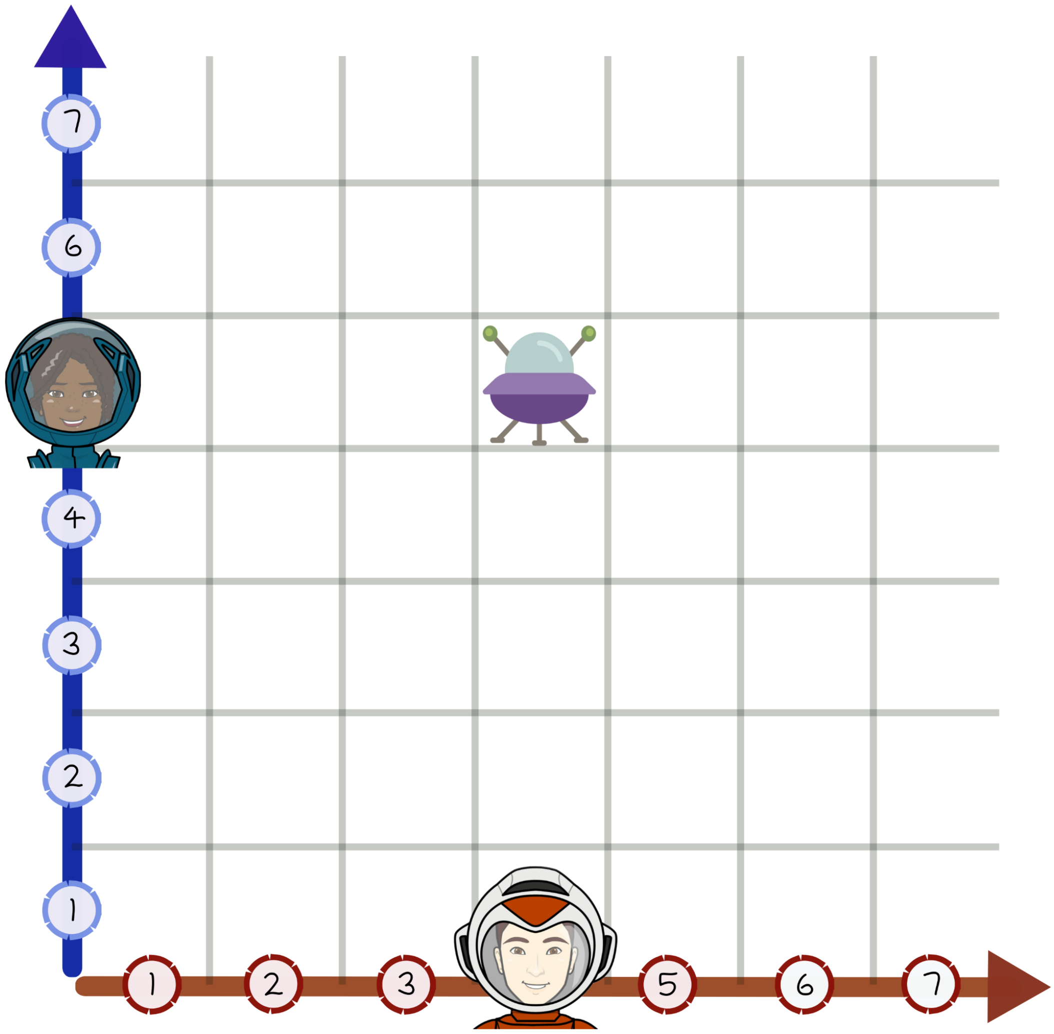


Your answer:

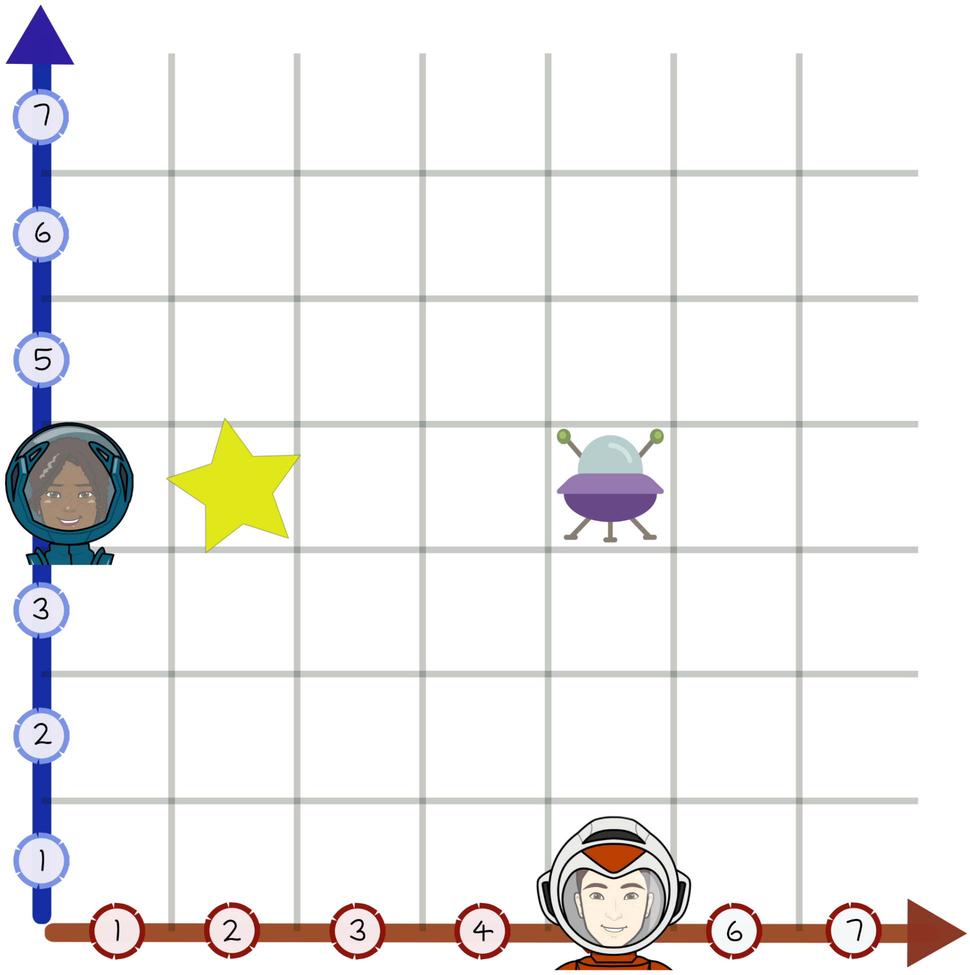
In the pictures below, the red astronaut can only move left or right. The blue astronaut can only move up and down.

If the red astronaut moves left or right, the spaceship will move left or right.

If the blue astronaut moves, the spaceship will move up or down.



5-1) In this picture, report which astronaut must move, so the spaceship can reach the star?

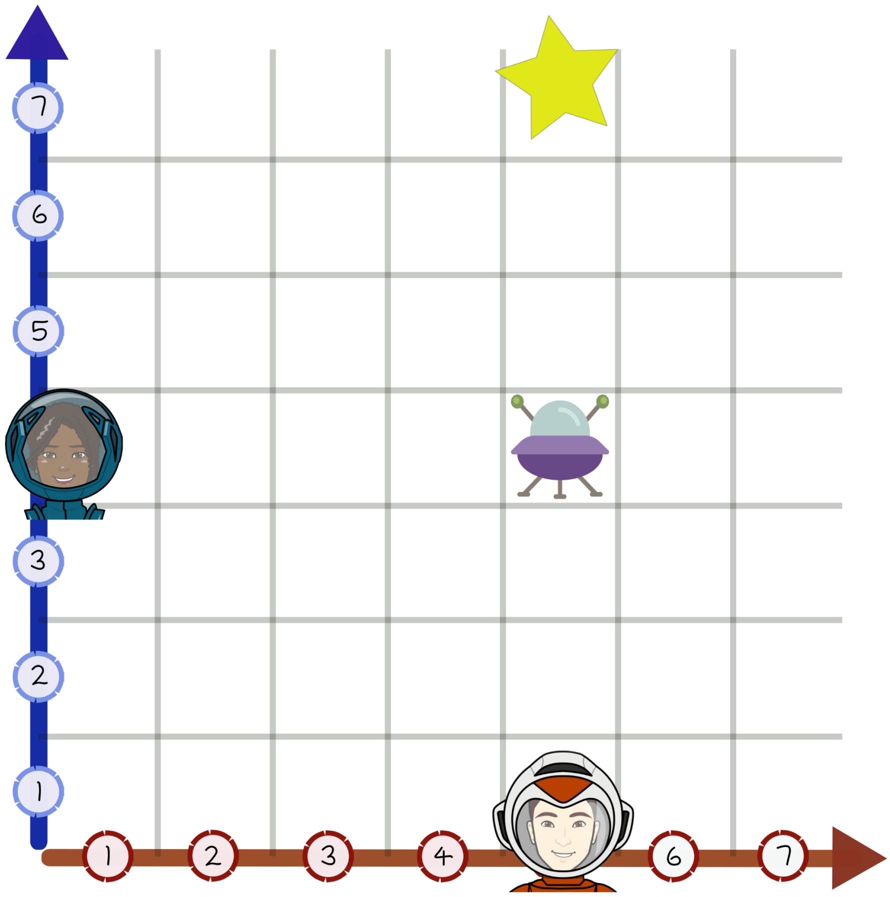


A) Only red astronaut should move

B) Only blue astronaut should move

C) Both astronaut should move

5-2) In this picture, report which astronaut must move, so the spaceship can reach the star?

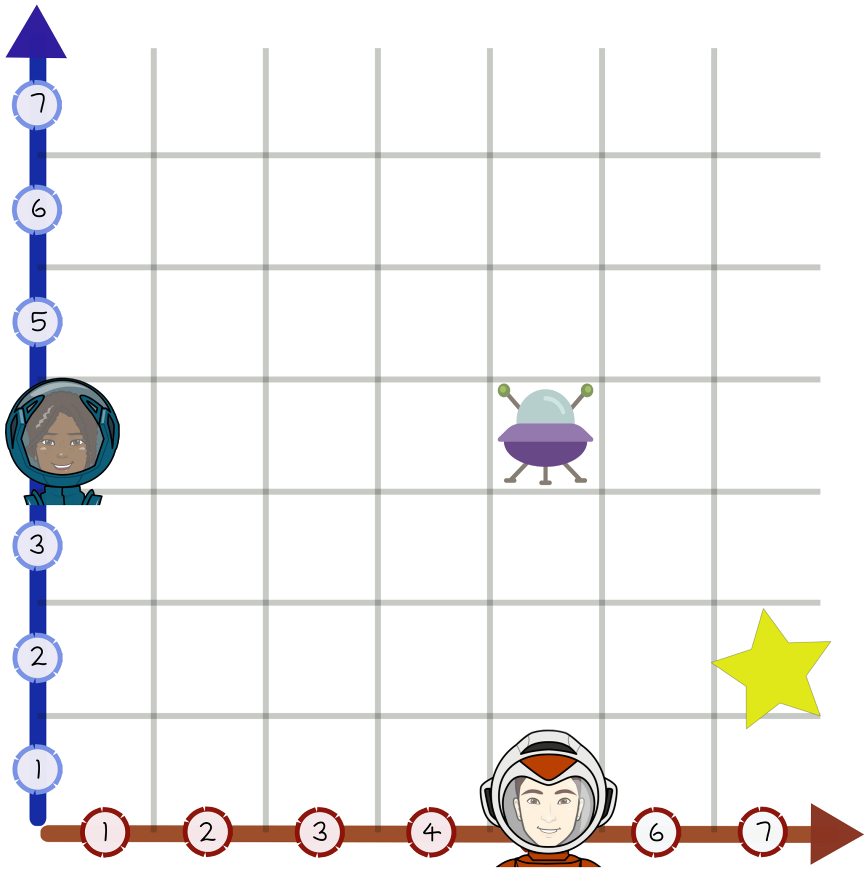


A) Only red astronaut should move

B) Only blue astronaut should move

C) Both astronaut should move

5-3) In this picture, report which astronaut must move, so the spaceship can reach the star?



A) Only red astronaut should move

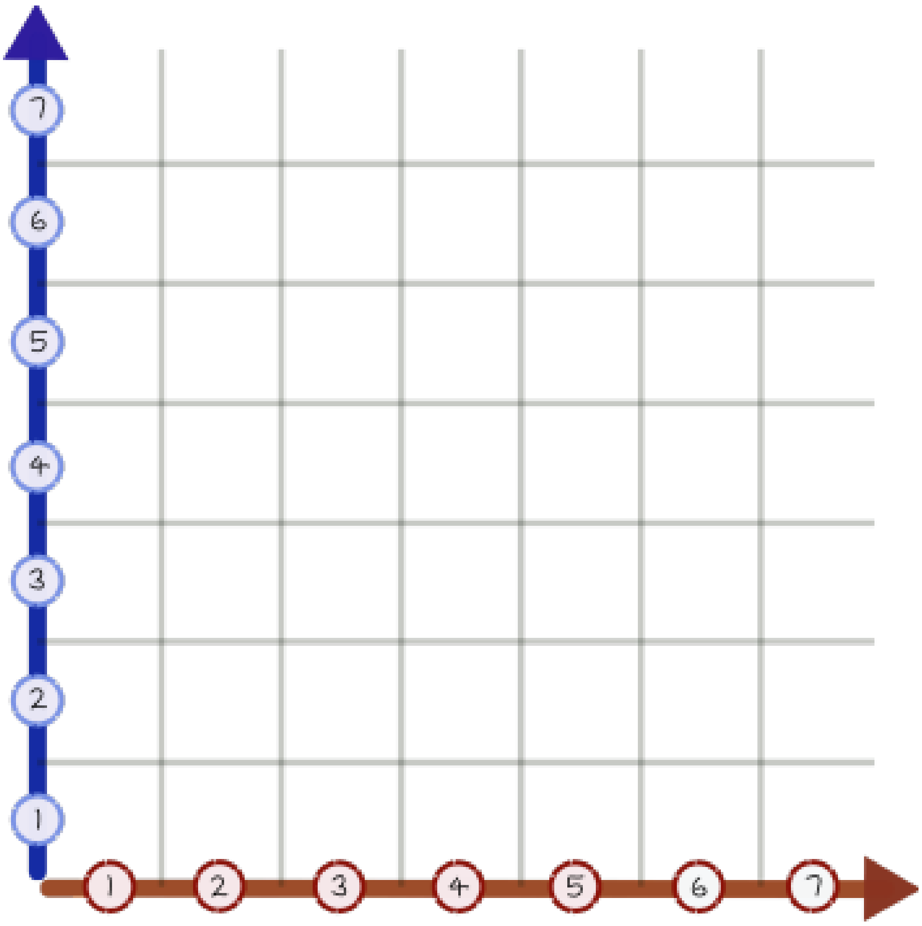
B) Only blue astronaut should move

C) Both astronauts should move

D) Both astronauts should move, it doesn't matter who goes first.

E) Both astronauts should move but the blue one should go first.

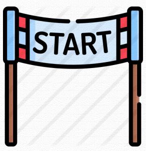
6) Write down why you think coordinate systems can be useful?



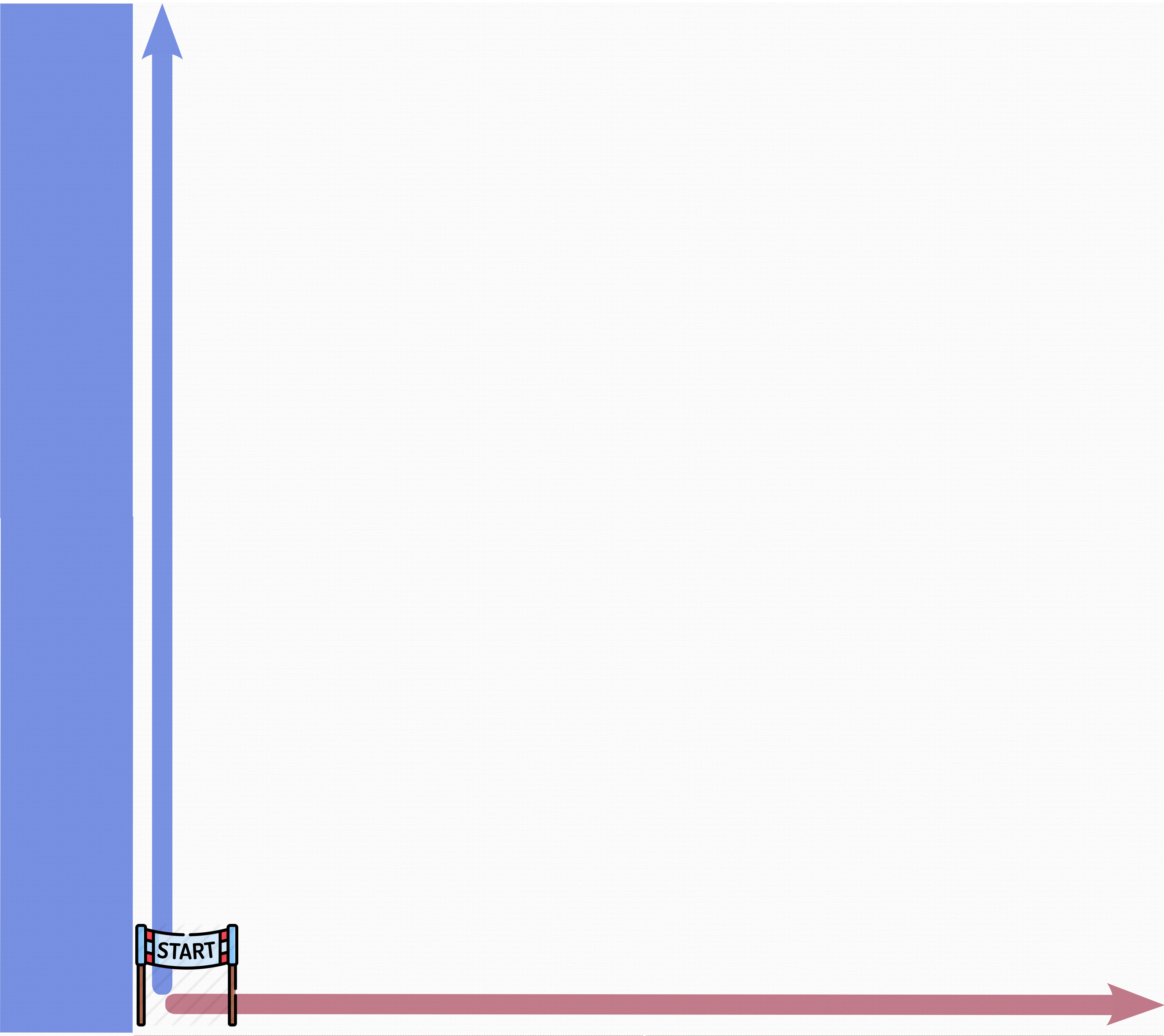
A coordinate system

Your answer:

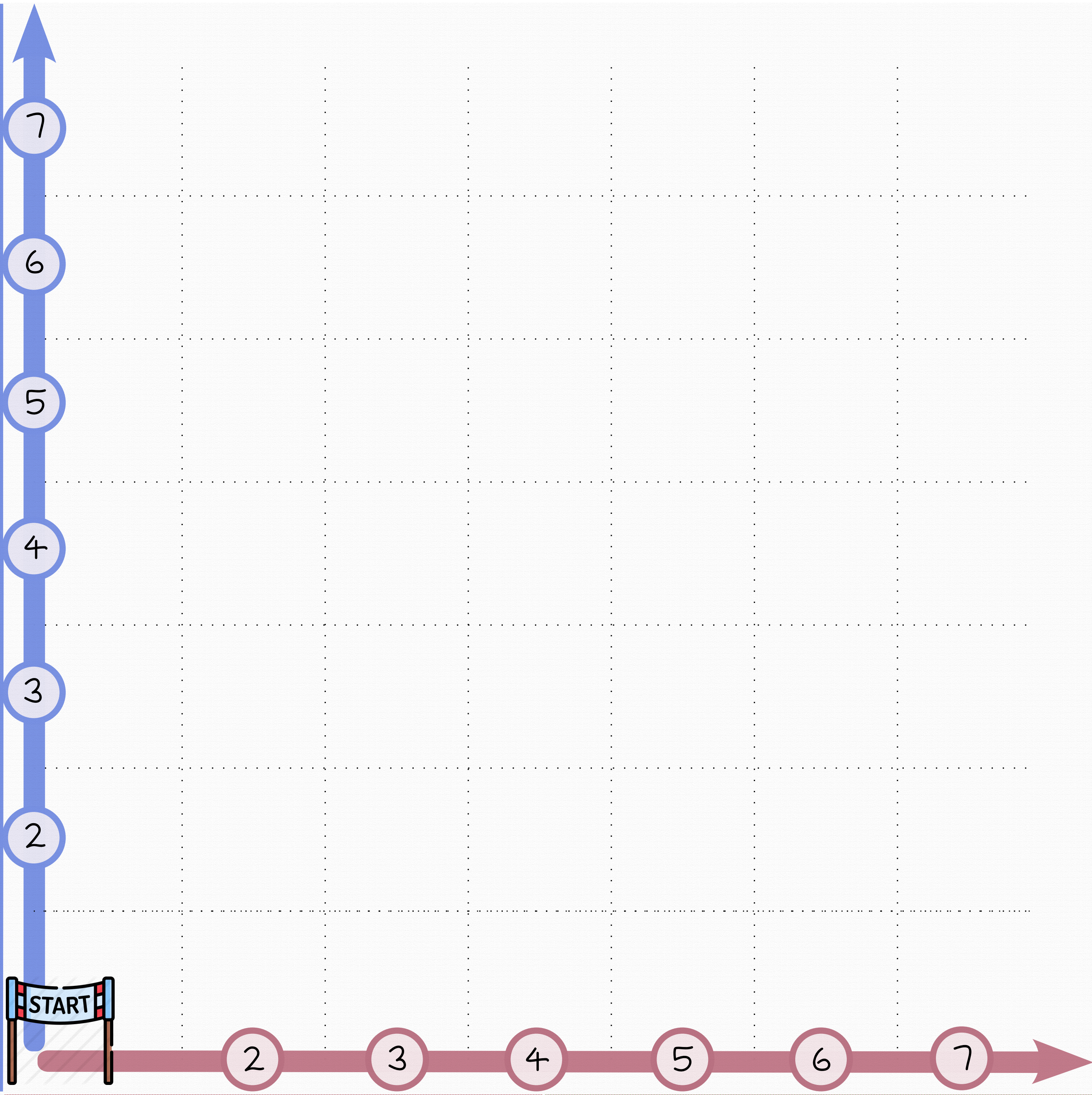
A.3 The physical maps for Cellulo robots



1



2



3

B Pre and post-test for measuring students' learning gain in regards to line slope topic

B.1 Pre-test

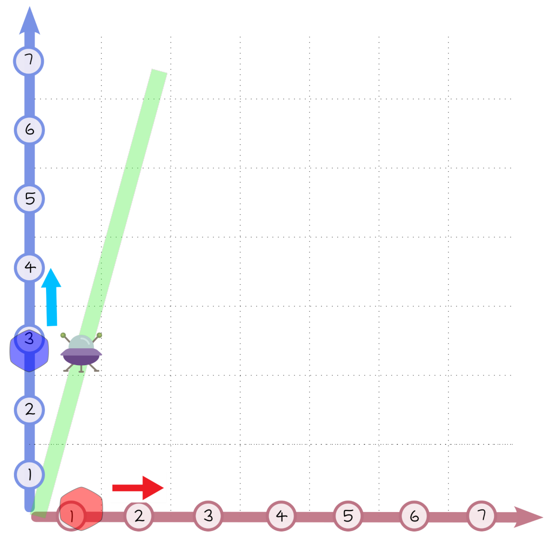
Name and Last Name :..

Group :......................................

Date:................................

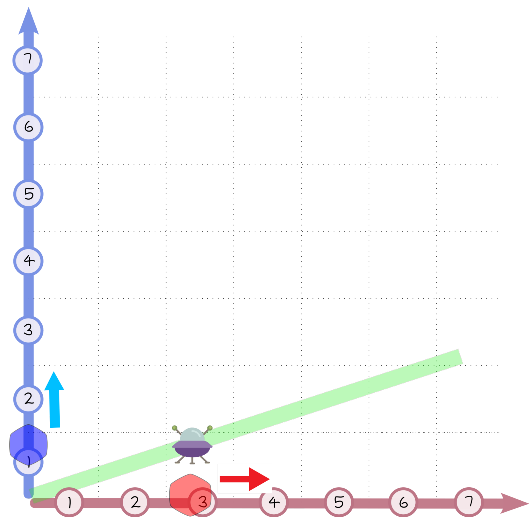
Q1) If the spaceship is supposed to move exactly on the green line below, which cellulo should go faster? (both cellulos will start together)

a) The red cellulo should go faster
b) The blue cellulo should go faster
c) It does not matter who goes faster
d) They should go on a same speed



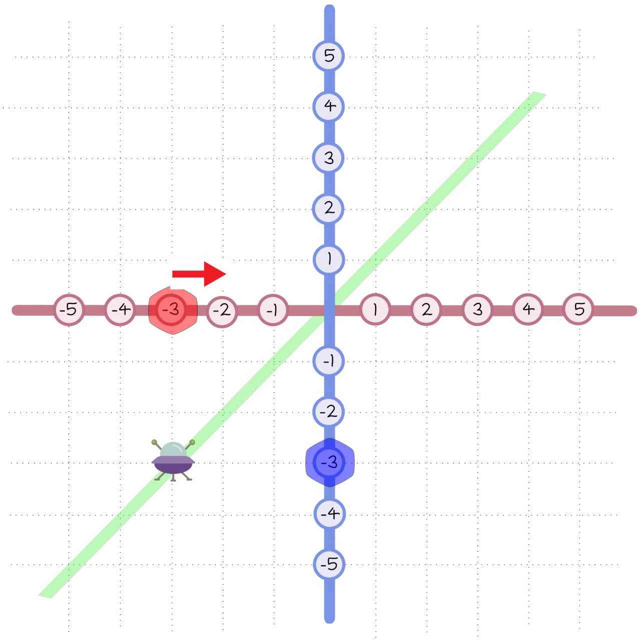
Q2)If the spaceship is supposed to move exactly on the green line below, which cellulo should go faster? (both cellulos will start together)

a) The red cellulo should go faster
b) The blue cellulo should go faster
c) It does not matter who goes faster
d) They should go on a same speed



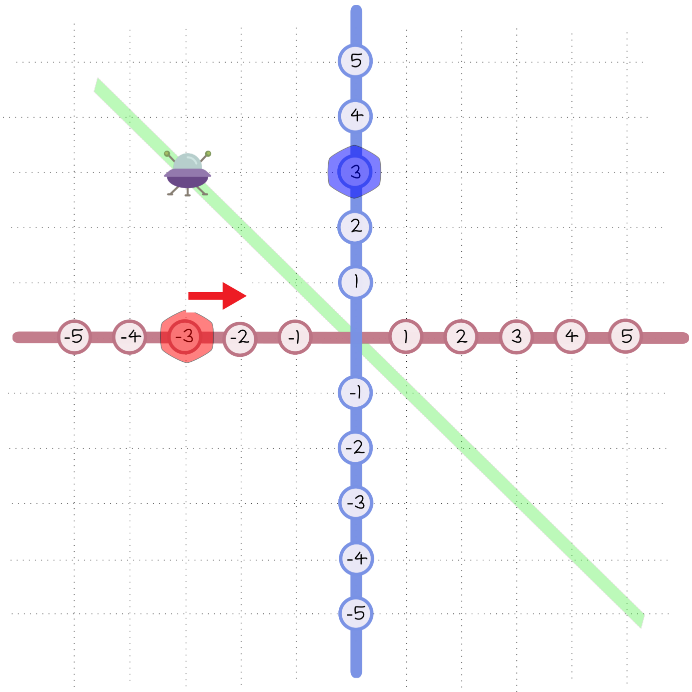
Q3) To ensure that the spaceship will always be on the line below, **when the red cellulo moves one unit to the right**, the blue cellulo:

a) Will go up by one unit
b) Will go down by one unit
c) Will go up by two units
d) It should not move

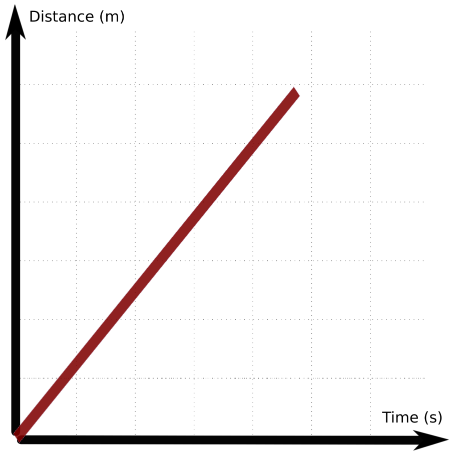


Q4) To ensure that the spaceship will always be on the line below, **when the red cellulo moves one unit to the right**, the blue cellulo:

e) Will go up by one unit
f) Will go down by one unit
g) Wil go up by two units
h) It should not move



Q5) The graph of Distance vs. Time of four cyclists at the start of a race is shown below. Which of them drove the fastest?



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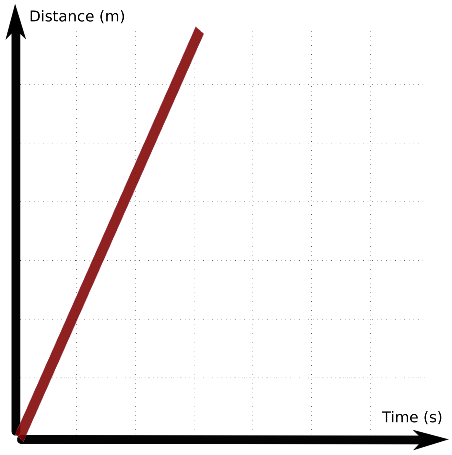

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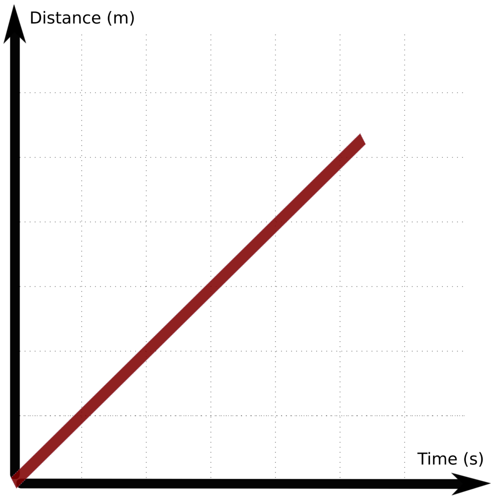

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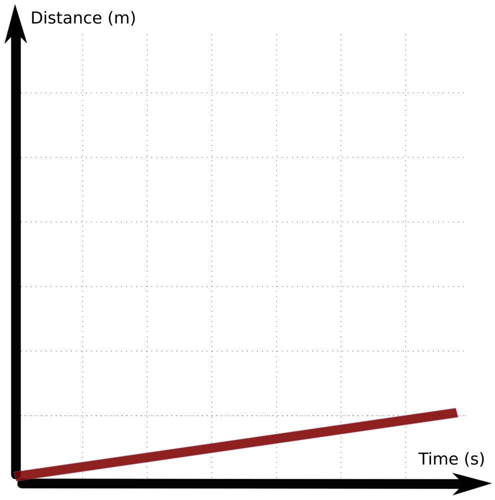


⬜

B.2 Post-test

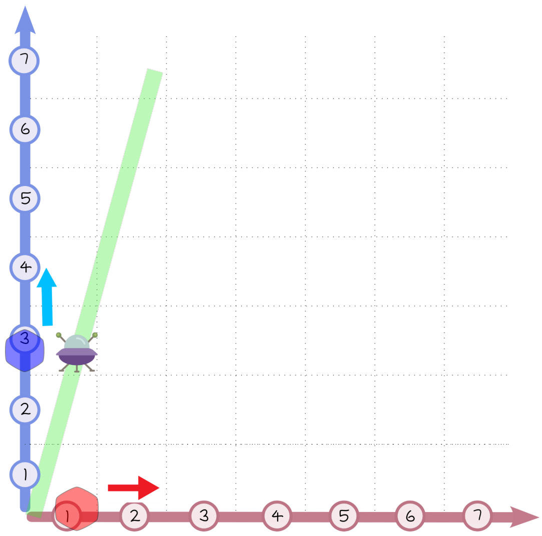
Your name :..

Group :.....................................

Date:................................

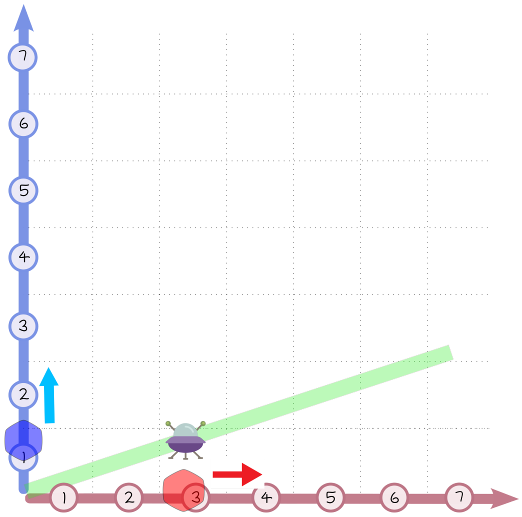
Q1) If the spaceship is supposed to move exactly on the green line below, which cellulo should go faster? (both cellulos will start together)

a) The red cellulo should go faster
b) The blue cellulo should go faster
c) It does not matter who goes faster
d) They should go on a same speed



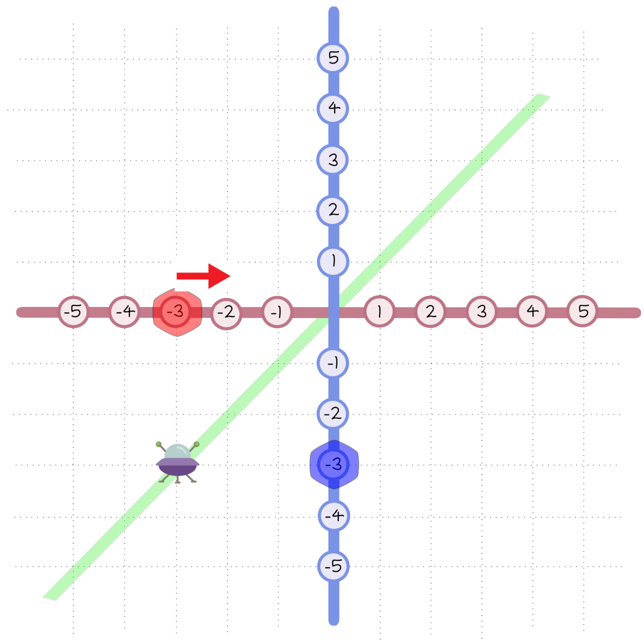
Q2) If the spaceship is supposed to move exactly on the green line below, which cellulo should go faster? (both cellulos will start together)

a) The red cellulo should go faster
b) The blue cellulo should go faster
c) It does not matter
d) They should go on a same speed



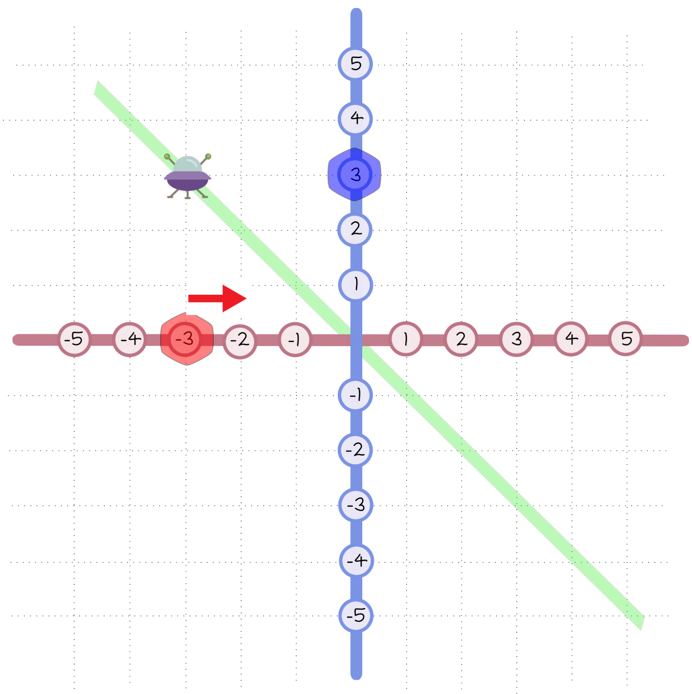
Q3) To ensure that the spaceship will always be on the line below, **when the red cellulo moves one unit to the right**, the blue cellulo:

a) Will go up by one unit
b) Will go down by one unit
c) Will go up by two units
d) It does not move



Q4) To ensure that the spaceship will always be on the line below, **when the red cellulo moves one unit to the right**, the blue cellulo:

e) Will go up by one unit
f) Will go down by one unit
g) Will go up by two units
h) It does not move



Q5) Match the correct line (A, B, C, D) to its description (there is an additional description):

Slope = 3 , Intercept= -3 Line: ....

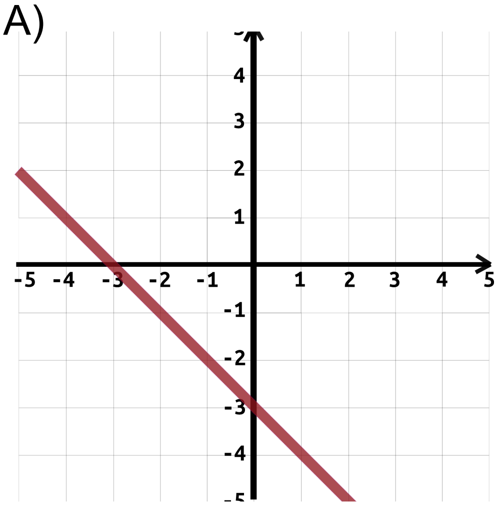
Slope = 1 , Intercept= 2 Line: ....

Slope = 1 , Intercept= 1 Line: ....

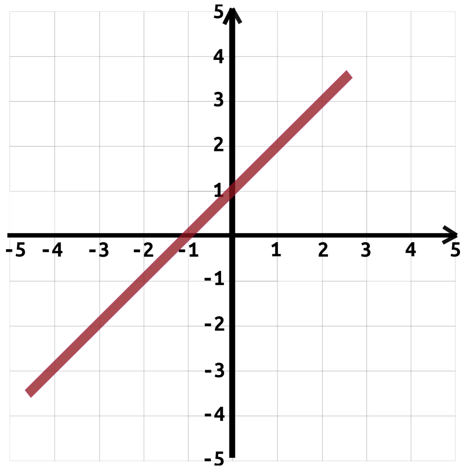
Slope = 1, Intercept= -3 Line: ....

Slope = -1, Intercept= -3 Line: ....

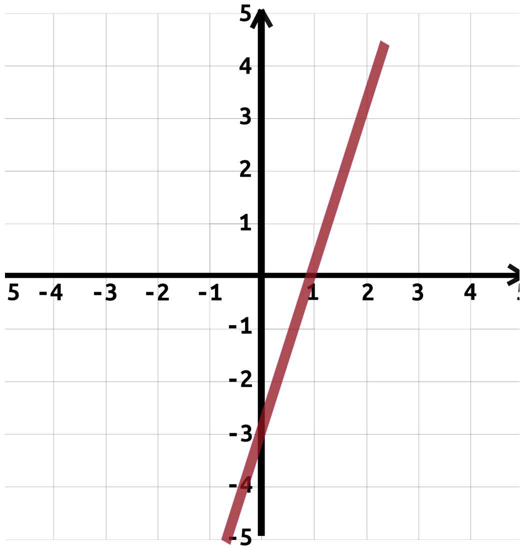
A)



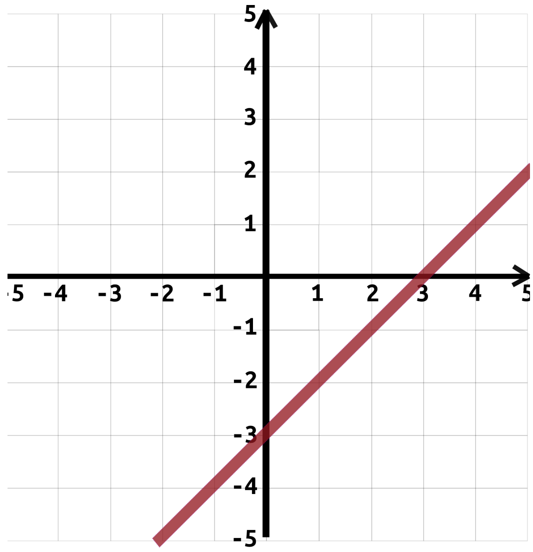
B)



C)

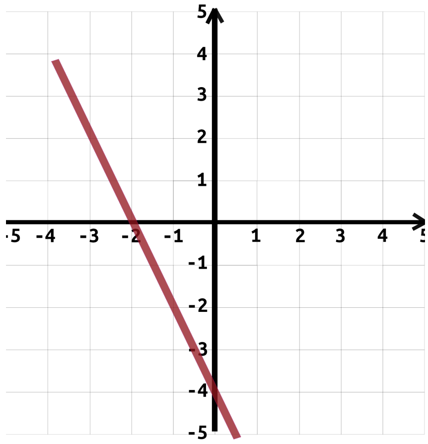


D)



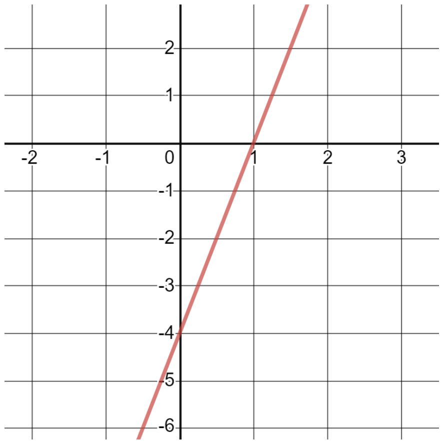
Q6) If you want to describe these lines to your friend in words, how would you say it? You can use slope and intercept to communicate with your friend.

1)



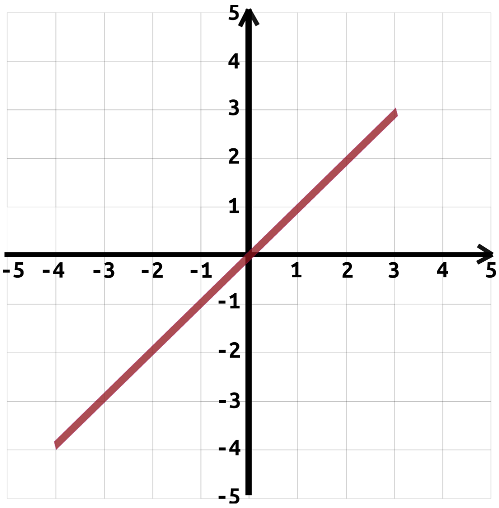
Slope: —------ Intercept: .....

2)



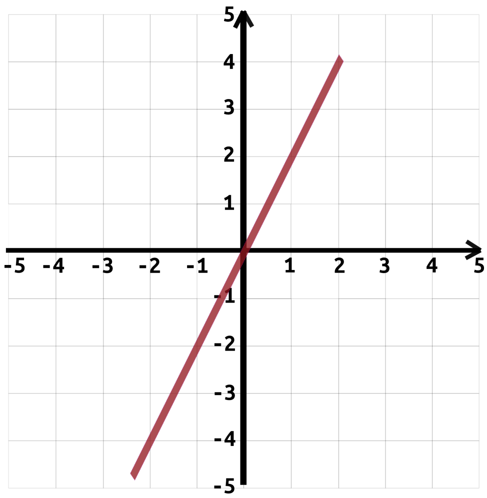
Slope: —------ Intercept:..........

3)



Slope: .... Intercept:..............

4)



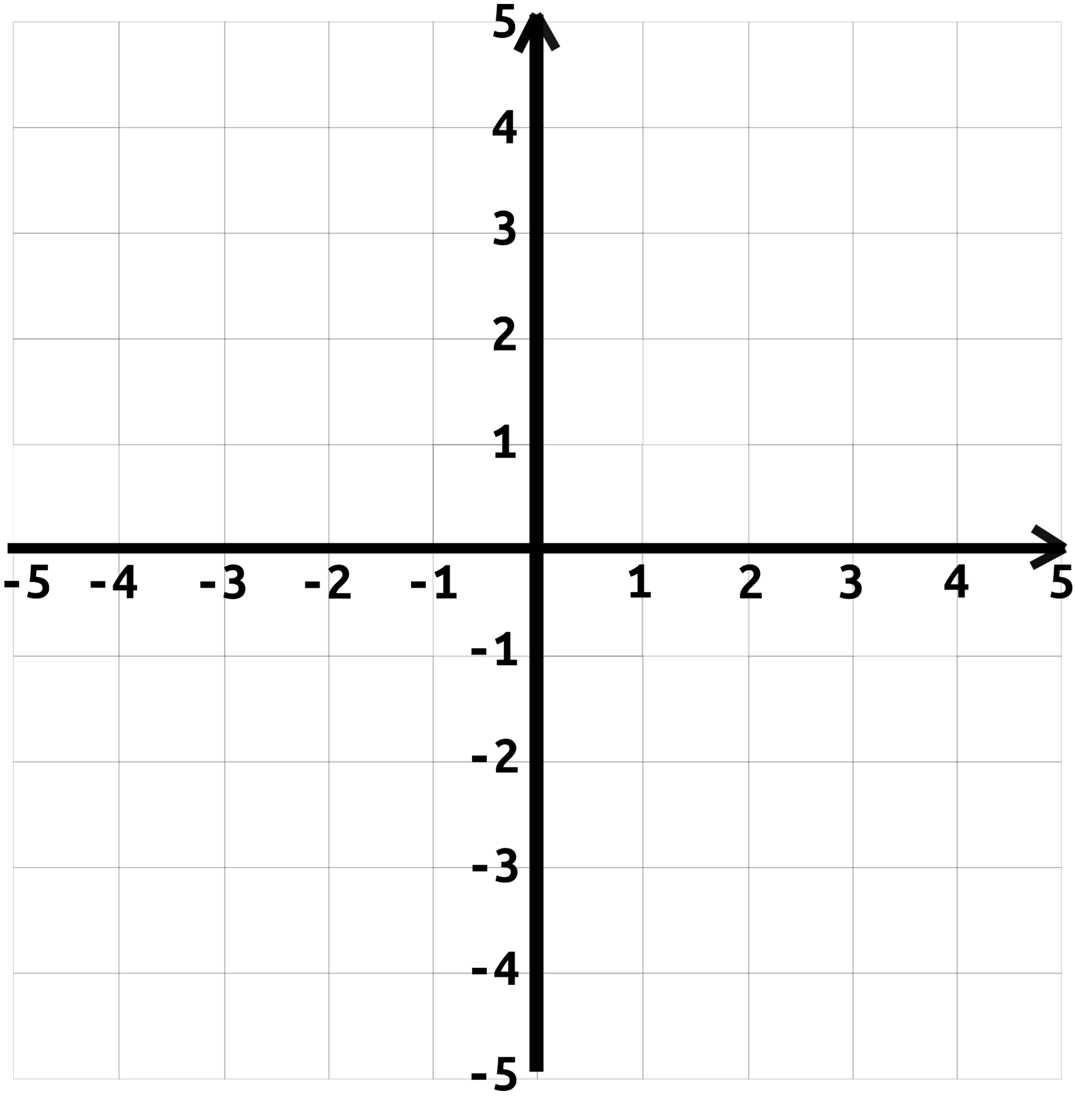
Slope: .... Intercept:..............

Q7) Here are the directions for three lines below. Draw the line for each indication:

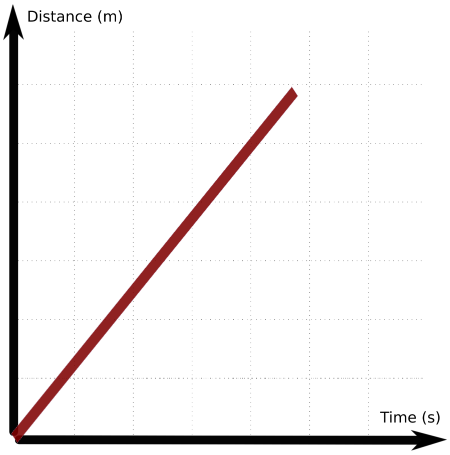
Line A: Slope: 2, Intercept 1

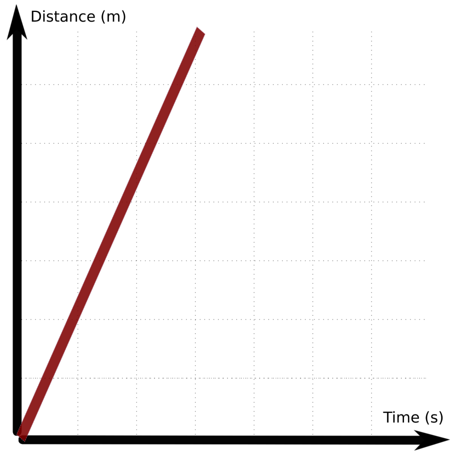
Line B: Slope -2, intercept 0,

Line C: Slope 1, intercept -1



Q8) The graph of Distance vs. Time of four cyclists at the start of a race is shown below. Which of them has moved the fastest?





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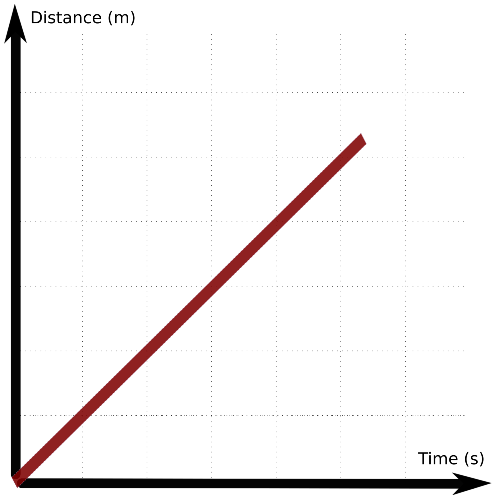

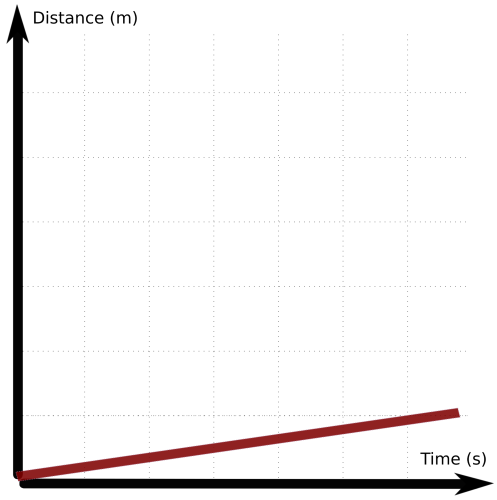

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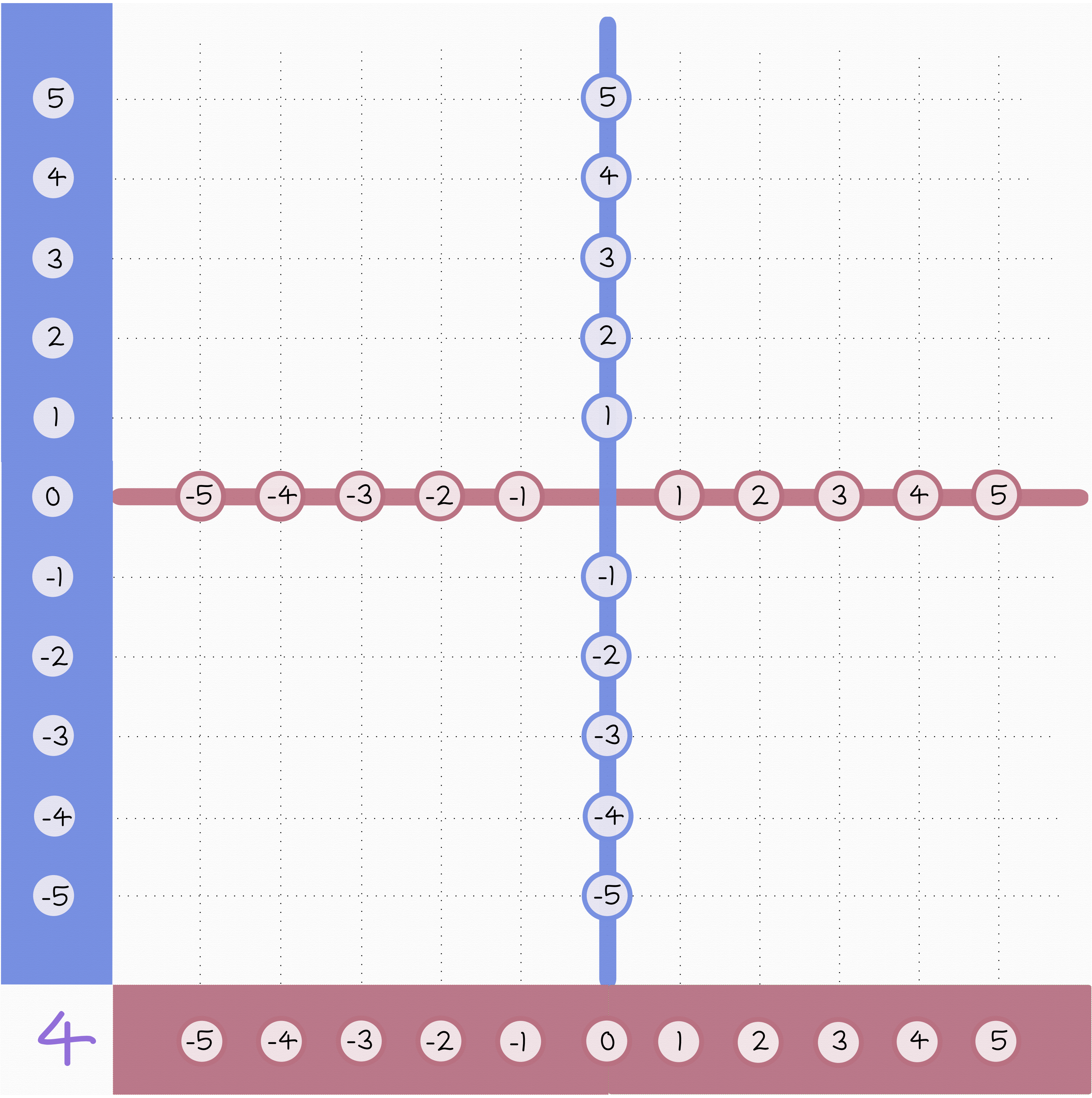
B.3 The physical map for Cellulo robots



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Sina Shahmoradi

Researcher in Learning Technologies, AI & Robotics in Education

Iranian, Living in Switzerland, holding permit B and 30 years old.

Summary

I am a Last year doctoral researcher at EPFL with specialization on learning analytics dashboards. By analysing twenty teachers' management patterns in classrooms and two-hundred students' activity patterns in a robotic math activity, I have extracted teachers' needs and most critical students' progress indicators which has inspired the design of a novel data-driven actionable teacher dashboard. The system has been tested in more than ten public and private schools across Switzerland. I am interested in *translational research* which directly benefits teachers and students.

I have a strong engineering background, specialized in applied machine learning, statistical data analysis and software engineering. I have developed a novel Fuzzy-based Sequential Pattern Recognition algorithm used in speech, text mining. I have developed and tested the usability of smart robotic systems directly with stakeholders in education and rehabilitation fields. I am interested in human-centered AI design and data science, especially with applications in education and social sciences.

Specific Skills

Expertise in learning science research with interest in classroom discourse analysis, designing learning dashboards, constructivist learning.

UX research with competence in mixed-methods, user observation, focus groups, A/B testing, affinity diagramming and experience in user-centered design.

Advanced data analytic: statistical data analysis, speech and text mining, time-series analysis, using R and Python.

Supervision of young learners and novice researchers in data sciences, learning analytic,software engineering.

Data visualization techniques with Tableau, Matlab, Python and R.

Applied machine learning with competence in regression techniques, decision trees, clustering techniques, sequential pattern recognition (Hidden Markov Model), neural networks and deep learning, fuzzy systems, using Matlab and Python

Database Management, with competence in SQL, MongoDB and Firestore.

Front-End Development, with competence in HTML,CSS,JS and experience in React JS, Flutter, REST APIs, D3.js.

Back-End Development, with competence in Django (Python), Node.js

Software/Robotic Engineering, especially Python, C++, ROS, Qt/QML

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Education

2018–Now **P.h.D in Robotics, Control and Intelligent Systems**, *CHILI Lab*, EPFL, .
Research Area: an intersection of three dynamic research areas of *Human-Computer-Interaction, Learning Analytics and Educational Robotics*.
Topic: I explore the effect of using learning dashboards in robotics classrooms and evaluate teachers' orchestration patterns. My project, part of an EU project, named ANIMATAS, aims to find the best ways to use learning analytics in robotic classroom based on classroom discourse. My Thesis in 3 Minutes
Contributions: designing research experiments, gathering more than ten hours speech data and more than two-hundred students' interactions with a robotic learning activity and their learning test results. Data cleaning, processing and statistical analysis using Python. Visualization of teachers' speech and students' activity in Python. Reporting the results based on teachers' feedback.
Monthly presentations and participating in several academic conferences, digital industry and robotic events, across Europe.
Supervisors: Prof. Pierre Dillenbourg, Dr. Barbara Bruno

2014–2017 **Master in Mechatronic Engineering**, *Artificial Creatures Lab (ACL)*, Sharif University of Technology.
Topic: I built wearable movement sensors (IMU+GPS with Micro-controllers) to track human lower-limb movement. I used the raw data to classify the participant's movement pattern (walking, running, stair climbing, sitting, etc).
I worked with different machine learning algorithms, like HMM or Fuzzy computing to develop a novel Fuzzy-based sequential machine learning model, called FEMM, for speech, handwriting recognition.
Contributions: gathering more than ten hours wearable sensor data from twenty subjects. Data cleaning and signal processing. Building classification models.
Supervisor: Prof. Saeed Bagheri Shouraki

2010–2014 **B.Sc. in Mechanical Engineering**, *K.N.Toosi University of Technology*, Iran, Special project: Detection of cardiovascular abnormalities. Time-frequency analysis of PCG heart sounds using Matlab.

Experiences

2019–2020 **Software engineer**, *CHILI Lab, EPFL*, Switzerland.
FROG is an open source platform for in classroom teaching focused on collaborative learning and experiential learning.
Contribution: creating a dashboard for teachers to monitor students' progress in a learning activity with educational robots.
Tech Stack: ReactJS+ HTML+ JS as front-end + NodeJS as backend + MongoDB as database + Qt/QML to interact with robots

2018-Now **Teacher assistant for several courses**, *EPFL*.
Courses: **Introduction to Visual Computing**, **Human Computer Interaction** and **Digital Education** courses. (Main teacher: Prof.Dillenbourg)
Responsibilities:
1) Guiding students in basics of software engineering (Git), programming digital games (Processing, Unity).
2) Guiding several teams of students to design learning activities with online learning software and test the efficacy of their design with empirical experiments.
3) Revising their assignments and helping teams in terms of providing up-to-date teaching materials.

2018-Now **Supervisor of semester projects**, *EPFL*.
I have supervised more than twelve master and semester students in performing their semester projects in computer science and robotics to build web/android applications, concerning educational robots.
I guided a team of four students for designing a set of learning activities with tangible programming setup and build an appropriate learning dashboard for teachers who managed the activities.

2017–2018 **Machine Learning Researcher**, *Djavad Mowafaghian Neuro-Rehabilitation center*, Iran, .
Project: Optimizing rehabilitation exercise program.
Contribution: I designed and implemented a fatigue status classification model for post-stroke patients, using two well-known classifiers: Hidden Markov Model (HMM) and Artificial Neural Network (ANN).
Contributions: gathering sEMG data from more than ten sbjects, cleaning and signal processing, feature extraction, data visualization, evaluating classification models using Python.
Supervisor: Prof. Saeed Behzadipour

2017–2018 **Teacher**, *Allameh Helli high school*, Iran, *Tehran, Iran*.
Teaching basics of robotics, electronics to students.
Guiding students to run mechatronic projects, like design and build a 3D printer.

Notable Project

2021–Now **Data Engineer**, *Association Tournesol*.
Tournesol is an open source platform to recommend high-quality public videos from Youtube by eliciting contributors' judgements on content quality.
My contributions so far has been:
1) Designing visualization features, like radar chart to show video scores.
2) Working on new score visualization features on a chrome extension.
3) Code review at front- and back-end.
Tech Stack: Docker + React (Typescript) + Redux + Vanilla JS + Django(Python) + REST API + d3.js

2019–Now **Creator of CelloRoom project**, *CHILI Lab, EPFL*, Switzerland.
CelloRoom is a platform including the first series of collaborative mathematics learning activities as an android application with tangible robots, called Cellulo.
I designed and technically implemented the first learning analytics dashboard for Cellulo robots as a web application.
I have used classical classification models to classify social level of teacher-student interaction based on classroom discourse. The results will be added to the dashboard to make teachers reflect on their teaching methods.
I have tested the usability and usefulness of the dashboard with more than twenty teachers and two-hundred students in Swiss schools.
For more information look at this video.
Tech Stack: Flutter as front-end + Firestore as database.

Services/Volunteer Works

2021–Now **Member of work-group to facilitate interface between learning research and entrepreneurs**, *LEARN Center, EPFL*.
In order to facilitate translational research, we propose initiatives at EPFL and Swiss Edtech Collider to motivate EPFL students pursuing Edtech entrepreneurship as their careers.
Two current initiatives involve studying EPFL students' interest to Edtech entrepreneurship and integrating computer science courses at EPFL with authentic educational data from Swiss Edtech startups.
We actively try to make a link between Swiss Edtech startups with researchers at EPFL, so they can benefit from learning sciences input as a way to improve their final products.

Winter 2019 **Co-organizer of ANIMATAS workshop**, *EPFL*.
I have co-organized the ANIMATAS workshop on **developing technologies in educational settings** in Switzerland for novice learning and robotic researchers. I was responsible for local logistics management of the organization and managing the plan and local coordination. I was the lecturer for a specific part of the workshop with the focus of designing orchestration tools for classrooms.

Summer 2021 **Co-organizer of ANIMATAS symposium**, *EPFL*.
I have co-organized the ANIMATAS symposium on Human-Machine Interaction in Educational Settings, in Switzerland with guests across the Europe. I was responsible for local logistics management of the organization and during the symposium I manged the plan and local coordination.

Summer 2022 **Management of Milonga social events**, *Architango, EPFL*.
I have been responsible for organising the Milonga events for the tango dance events with more than one-hundred participants weekly.

Awards

2010 Bronze medal in Skills Iranian National Competition for Data analytic (with Excel) and Software applications

2014 Part of the winner team in design for sustainability competition, K.N.Toosi University of Technology, Iran

Languages

Farsi	**Mothertongue**	
French	**Intermediate**	*Work Proficiency*
English	**Fluent**	*Fluent*

Related Courses

Digital Education and Learning Analytic	*EPFL*
Machine Learning for Engineers	*EPFL*
Applied Data Analysis (audit)	*EPFL*
Entrepreneurial Opportunity Identification and Exploitation	*EPFL*

Referees

Pierre Dillenbourg **pierre.dillenbourg@epfl.ch** *Vice Associate President of Education at EPFL*

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