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ORIGINAL RESEARCH

Pair Interactions and Emergent Roles in Problem-Solving with Modular Robotics in Primary Education

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Abstract
The ability to solve problems collaboratively has become a crucial skill for success in an increasingly complex world. This study explores pair interactions and the emergence of collaborative roles among primary school pupils engaged in problem-solving tasks using modular robotics. We identify three distinct cooperative forms: co-construction, acquiescent co-elaboration, and one-sided manipulation. Our findings show that pairs who relied on one-sided manipulation or had little interaction struggled more with task resolution (RQ1). In terms of roles, participants initially acted as explorers but gradually adopted more defined roles such as proposer, critic, hand, or follower. We found that pairs with complementary and balanced roles showed better coordination and outcomes (RQ2). Finally, we identified four main collaboration challenges (competitive behaviors, lack of leadership, communication gaps, and task misinterpretation) impacting efficiency (RQ4). These findings highlight the need for structured support in educational robotics to foster equitable collaboration, clarify task understanding, and promote effective role-sharing among young learners.

Keywords Pair problem solving · Cooperation · Educational robotics · Co-construction · Co-elaboration · Communication

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1 Introduction

The ability to solve problems collaboratively has become essential for success across various personal and professional sectors, as it is a core competence required for navigating the complex, ill-structured challenges of modern workplaces and societies (Chai et al., 2023). Exhibiting proactivity as a collaborative team member, alongside strong verbal communication and problem-solving competencies, is essential in technology-mediated contexts (McGunagle & Zizka, 2020; Zhou & Ye, 2024), particularly in the utilization of robotic systems (Kurtz & Kohen-Vacs, 2024) and artificial intelligence for human-AI problem resolution (Schelble et al., 2024). Collaborative problem solving (CPS) is essential in disciplines such as engineering and technology, where innovation increasingly depends on diverse groups collaborating to develop solutions. Consequently, comprehending the dynamics of individual collaboration and problem-solving in real-world contexts is essential for educational research. CPS in education has been examined across various computer-supported collaborative learning (CSCL) tasks and scripts regarding students' self-regulation (Miller & Hadwin, 2024), social interaction (Asfani & Chen, 2025), critical thinking (Xu et al., 2023), and learning performance (Tian & Zheng, 2024).

The present work focuses on students' CPS skills in the context of educational robotics. OECD (2017) defines CPS "as the capacity of an individual to effectively engage in a process whereby two or more agents attempt to solve a problem by sharing the understanding and effort required to come to a solution and pooling their knowledge, skills, and efforts to reach that solution" (p. 5). Hesse et al. (2015) underline that CPS is a very promising activity that builds upon various social and cognitive skills and can be measured and taught in educational contexts. OECD (2017) proposes the assessment of CPS by evaluating the following competencies: (i) establishing and maintaining shared understanding; (ii) taking appropriate action to solve the problem; and (iii) establishing and maintaining team organisation. CPS is of crucial importance to face technology challenges in which competencies from different teammates are required to think critically (Xu et al., 2023) and to regulate the complexity of CPS in technology-rich environments (Polyakova et al., 2024). The study of CPS has been developed in the last few years in computer science education (Priemer et al., 2020; Umutlu, 2021) and with an increasing number of studies in educational robotics (Ates & Aktamis 2024; Avcı, 2024; Chevalier et al., 2022; Çakır et al., 2021). Over the past five years, classroom settings have increasingly incorporated educational robotics to improve problem-solving and collaboration skills. The meta-analysis of Zhang and Zhu (2024) observed a positive effect of educational robotics in creativity and problem-solving in kindergarten but also primary and secondary students. The research emphasises the value of educational robotics for promoting hands-on, interdisciplinary learning experiences that foster teamwork.

Despite growing interest in CPS, most studies focus on screen-based environments, leaving a gap in understanding how young learners interact around tangible, modular robotics tasks. This study addresses this gap by focusing on pair-based CPS, which offers a controlled context to examine fine-grained CPS processes.

2 Educational Robotics in STEM Education

Educational robotics encompasses a wide range of pedagogical approaches, from guided activities to ill-defined problem solving (Atman Uslu et al., 2022; Komis et al., 2017). Our study is situated within the latter, focusing on the use of robotics as a tool for children to engage in problem-solving through manipulation and social interaction, consistent with the principles of constructivism. According to Zhang and Zhu (2024), educational robotics "essentially a constructionist tool which students interact with and utilise their knowledge and experience to solve real problems" (p. 1540).

Ouyang and Xu (2024) found that incorporating robotics into primary science, technology, engineering, and mathematics (STEM) curricula significantly improved students' cognitive flexibility and engagement in collaborative tasks. Similarly, Xu et al. (2024) observed that robotics-based activities promote co-construction of knowledge and negotiation of roles among students in problem-solving contexts. These findings suggest that educational robotics supports individual learning and creates authentic opportunities for students to develop key 21st-century skills such as cooperation and communication.

Educational robotics is also an opportunity to evaluate CPS from the perspective of learning theories that are important for the study. In relation to self-efficacy theory, educational robotics permits observing students' willingness to engage with CPS (Jaipal-Jamani, 2024). The social nature of CPS in robotics also aligns with social constructivism, where knowledge is co-constructed through peer interaction and tangible engagement with educational robotics (Pelizzari et al., 2024). Activity Theory further deepens this understanding by framing the robotics classroom as an evolving system in which tools, rules, and community mediate collaborative outcomes (Romero & Barma, 2024). In this study, from this theoretical perspective, we aim to evaluate the evolution of collaborative roles within these pairs of learners, identifying the shifts in role adoption as the tasks progressed.

3 Assessment of CPS with screen-based and Tangible Objects

Studies on collaborative problem-solving (CPS) in screen-based learning environments have advanced significantly over the last decade, supported by learning analytics and diversifying CPS tasks for evaluation in computer-based environments (Chevalier et al., 2022; Çakır et al., 2021). In this study, CPS is analysed through a task mediated by "visuo-spatial constructive play objects" (VCPOs; Ness & Farenga, 2016), a type of constructible playful objects that include Lego bricks but also modular interactive objects such as the modular robots in this study (Ates & Aktamis 2024; Avcı, 2024; Kalmpourtzis & Romero, 2024, Lin et al., 2024). Modular robotics are relevant for the study of CPS because they enable hands-on, embodied interactions that make collaborative problem-solving processes observable in physical space. Their open-ended and constructible nature allows researchers to capture rich multimodal behaviours such as manipulation, negotiation and coordination, which are central to understanding how young learners collaborate in real-world settings in interaction with tangible artefacts. However, the analysis of CPS through VCPOs is still limited and faces challenges in identifying appropriate observables to develop behavioural learning analytics methodologies for non-screen interactions with VCPOs (Köhler & Romero, 2023). This study engages students in educational robotics to examine the specificities of manipulative pair problem-solving, the emergence of roles within CPS tasks, and the types of difficulties primary education learners encounter in these tasks.

In order to support students' development of CPS through educational robotics activities, we need to understand the interaction through cooperative activities as a process (Pásztor-Kovács et al., 2023). For this objective, we examine students' interactions in a CPS activity with educational robotics. Students' interaction includes the manipulation of the robots, their emerging roles, and their verbal exchanges. In this paper, we closely examine students' interactions in a CPS activity. We analyse the CPS process through the learners' manipulations, emerging collaborative roles, and problems throughout their interaction.

To meet these goals, this study aims to examine the learners' pair dynamics in CPS using educational robotics. We focus on how physical actions and conversations combine to shape learning, and they aim to uncover the intricate ways learners interact with modular robotic systems. This approach allows us to improve our understanding of how teamwork skills develop through practical, hands-on activities and how these skills can be best supported and evaluated in primary education settings.

3.1 Collaborative problem-solving Activities with Educational Robotics

Numerous scholars have explored the dimensions of collaboration, problem-solving, and CPS within the context of educational robotics activities. Ardito et al. (2020) investigated the development of these skills among sixth-grade students participating in a six-week LEGO robotics program. Similarly, Yuen et al. (2014) focused on the dynamics and interactions among elementary and middle school students during a summer robotics camp, specifically within their collaborative work sessions. Denis and Hubert (2001) analysed CPS in educational robotics activities, proposing regulatory measures for optimising learner interactions. Echoing this perspective, Atmatzidou and Demetriadis (2012) advocated for the use of collaboration scripts to structure group interactions during educational robotics activities. Despite the challenges of CPS robotics activities, the students show important engagement during these activities (Romero & Barma, 2024). These studies collectively underscore the critical role of structured interactions in enhancing the effectiveness of CPS activities.

CPS activities can show an important difference in the role definition. While some CPS activities explicitly define roles, providing learners with predefined sequences to facilitate structured collaboration, others allow CPS roles to emerge spontaneously, offering no scripted roles to participants. For instance, the CreaCube task (Romero et al., 2019) does not assign specific roles to learners and allows for multiple solution paths. We categorise such tasks as ill-structured problems, defining them as "questions, case studies, or scenarios that do not have a definite right or wrong answer" (Snyder & Snyder, 2008). The CreaCube task is intentionally designed as ill-defined, requiring participants to define the problem, generate multiple solutions, and evaluate their effectiveness. This type of task permits studying collaborative dynamics because it necessitates communication, negotiation, and the co-construction of knowledge through the manipulation of educational robots. The use of modular robotics, in this context, allows for open-ended exploration and multiple possible solutions, providing a context for observing how pairs of learners coordinate their actions, manage disagreements, and advance towards one of the potential configurations solving the problem. This approach aligns with a social constructivist perspective in educational robotics (Zhang & Zhu, 2024), where problem-solving is viewed as a process of co-construction.

Research in this domain typically adheres to two perspectives: the emerging roles perspective, where roles developed spontaneously are central to the activity, and the scripted roles perspective, which posits that assigning roles can enhance collaborative learning (De Wever & Strijbos, 2021) if they are defined in a flexible way and can evolve according to the task requirements (He et al., 2023) without limiting the students' engagement (Chiu, 2001).

3.2 Analysis of Pair Interactions and Emerging Roles in Collaborative problem-solving

In CPS environments, the analysis of student interactions, emerging roles, and encountered challenges is critical. Strijbos (2009) developed the Virtual Math Team (VMT) coding scheme to rigorously examine pair communication, interaction, and collaboration within such settings. Despite the inherent complexity of analysing verbal interactions, Strijbos delineates the interaction processes into three distinct dimensions: conversational,social, and problem-solving. Gilly et al. (1988) followed by Baker and Andriessen (2022) identify four principal forms of interactive dynamics in learners in pairs, which include acquiescent co-elaboration, co-construction, confrontational, and contradictory confrontations. Extending this taxonomy, Baker (2002) proposed eight specific forms of verbal cooperation that manifest through combinations of symmetry/asymmetry, agreement/disagreement,and alignment/misalignment. These dimensions (symmetry, agreement, and alignment) are fundamental in determining the dynamics of pair interactions in CPS activities. This study applies Baker's framework to explore the forms of cooperative manipulation in the CreaCube task. Our adaptations of Baker's models aim to elucidate the complex interplay of factors that influence effective collaboration in educational settings, particularly within tasks designed to foster problem-solving skills.

Understanding the emergent roles within CPS is crucial for comprehending individual contributions and interaction patterns among students. Strijbos and Weinberger (2010) emphasise the significance of analysing these roles to elucidate how group members facilitate progress and interact within educational settings. Typical roles identified include the 'facilitator,' who supports participation and promotes group harmony; the 'proposer,' who introduces new ideas; the 'supporter' and 'critic,' who assess these ideas by exploring their merits and drawbacks; and the 'recorder,' who documents the group's progress (Chiu, 2001). Atmatzidou and Demetriadis (2012) have identified distinct roles such as 'programmer,' 'constructor', 'researcher,' and 'team manager' in the context of educational robotics, each uniquely contributing to the task at hand. This framework is instrumental in dissecting the dynamics of group interactions and enhancing the efficacy of collaborative learning environments.

Different studies have identified several factors that can adversely affect the dynamics of CPS and decision-making processes. Variables such as group size, task complexity, general cooperation, and the presence of non-contributing individuals, often referred to as 'free riders', can compromise the efficacy of CPS, as highlighted by Guazzini et al. (2018) and He et al. (2023). Furthermore, Sun et al. (2020) identified specific behaviours that undermine CPS activities, including intrusive actions like interrupting or talking over others, non-responsiveness, derisive comments or rudeness towards peers, expressions of withdrawal from the task, lack of focus on the task or assigned roles, and initiating or participating in off-topic discussions. These findings suggest that both task-specific factors and individual behaviours critically influence the effectiveness of student collaboration, potentially impeding the successful achievement of collective goals.

4 Originality, Rationale, and Significance

This study contributes original insights into the field of collaborative problem solving by examining how young learners engage with modular robotics in unstructured, hands-on tasks using visuo-spatial constructive play objects (VCPOs; Ness & Farenga, 2016). While CPS has been widely studied in digital environments, there is limited research addressing how these processes unfold in non-screen, tangible contexts. The rationale for this study lies in addressing this gap by providing an in-depth behavioural analysis of pair interaction patterns and emergent roles during physical collaboration. The use of modular robotics as a CPS medium is particularly significant, as it introduces a tangible, interactive component that requires negotiation, role distribution, and real-time adaptation due to the material limitation using modular robotics.

5 Methods

We conduct a mixed-methods interaction analysis approach to examine how learners in pairs engage in collaborative problem-solving, the roles they assume, and the challenges they encounter during the CreaCube activity. We chose to focus on pairs of learners, rather than larger groups, to closely observe and track the CPS process. This structure maximizes the opportunity for both participants to be actively engaged in the task. The analysis is developed through the video recording of the creative problem-solving task and the subsequent analysis of the coding schema applied to the video.

Video analysis serves us in this study as a multimodal data source capturing learners and robot interaction. Following the methodological principles articulated by Heath (2025), we treat video not simply as a record of events, but as a resource for the fine-grained analysis of social action, enabling us to observe interaction as it unfolds in real time and within the material environment of the activity. Consistent with the learning sciences tradition outlined by Goldman et al. (2014), video research allows us to trace learning as a process situated in activity, embedded in context, and mediated by tools and social relationships. The interaction analysis is structured around a coding schema that integrates emerging collaborative roles specific to the CreaCube context, drawing on and adapting categories from Cassone et al. (2021) and Chiu (2001). The coding process is applied to the video-recorded problem-solving sessions, allowing us to systematically examine patterns of collaboration and interactional dynamics as learners engage with each other and the modular robot cubes across the activity. We choose to use modular robotics for facilitating hands-on, embodied interactions that make collaborative problem-solving processes directly observable in a physical space. This tangible, non-screen-based context permits study collaboration dynamics that are not fully captured in purely digital environments, but require the observation of human-robotic interaction.The open-ended and constructible nature of these systems allows researchers to observe the behaviors such as manipulation, negotiation, and coordination, which are central to understanding CPS in real-world settings.

The problem-solving task was intentionally designed to be ill-structured. Unlike well-defined problems with a single correct solution, ill-structured problems lack a clear path to resolution, requiring participants to define the problem, generate multiple solutions, and evaluate their effectiveness (Romero et al., 2022). This type of task is particularly valuable for studying collaborative dynamics because it necessitates extensive communication, negotiation, and the co-construction of knowledge. The use of modular robotics, in this context, allows for open-ended exploration and multiple possible solutions, providing a rich dataset for observing how pairs coordinate their actions, manage disagreements, and create a shared understanding to reach a final outcome. This approach aligns with a social constructivist perspective, where problem-solving is viewed as a process of co-construction.

In the first task, participants assemble four pre-programmed cubes—a white motor cube, a red inverser cube, a black distance sensor cube, and a dark blue battery cube—to construct a vehicle that navigates from a red to a black point, marked either on a mat or by tokens on the table. The second task replicates the conditions of the first, with participants instructed to reassemble the cubes to either replicate or modify the initial vehicle design. We conduct both tasks under uniform instructions and record them for analysis.

To achieve this, we adopt a micro-analytic approach that considers both verbal and non-verbal interactional features, including speech, gestures, gaze coordination, and manipulative actions with the cubes. By analyzing these multimodal interactions, we aim to understand how participants construct collaborative engagement in real-time.

The following research questions drive the study:

- RQ1: Throughout the CreaCube activity, what are the pairs manipulative cooperative forms?
- RQ2: What collaborative roles emerge throughout the CreaCube activity?
- RQ3: What kind of difficulties did participants confront throughout their collaboration in the CreaCube activity?

5.1 Context and Participants

This study was conducted within the specific French educational context, which is relevant to understanding the approach to problem-solving. Recent data from the Trends in International Mathematics and Science Study (TIMSS) indicates that French students' math performance is below the European average. Only 3% of French students reached an advanced level in mathematics, compared to an 11% international average. In response to these findings, there's a growing push in France to explore alternative pedagogical methods for teaching mathematical procedures, with a particular focus on problem-solving through the use of tangible artifacts. In this context, our study aims to evaluate CPS through a modular robotic task. A sample of 12 primary school pupils (8 males, 4 females), aged 7 to 8, from a primary school in Nice, France, participated in the study. Pairs of students were formed based on a random assignment of pupils from a single class. This process resulted in two mixed-gender pairs and four same-gender pairs. To control the prior level, we identified that any of the participants had engaged priorly in the use of modular robotics. The study was approved by the ethical committee of Université Côte d'Azur (CER2019-6), and the parents signed for the consent of the children engaged in the study.

5.2 Data Analysis

We used the Advene video annotation and hypervideo authoring software (https://www.advene.org/) for the qualitative analysis of the recorded pair interactions. We scrutinised the video footage for each of the six pairs to assess the interactions between participants. Initially, the authors familiarised themselves with the recordings' content, then conducted a preliminary analysis using inductive coding to identify key manipulations and verbal statements (Boyatzis, 1998). Our analysis of the pair interactions was based on a coding schema designed to capture specific verbal and non-verbal behaviors occurring during the task. A deductive coding approach was adopted (Crabtree & Miller, 1999), guided by the forms of cooperative manipulation, adapted from Baker (2002), and the model of emerging collaborative roles in CreaCube, based on frameworks from Cassone et al. (2021) and Chiu (2001). Two pilot activities, including an exchange immediately after the CPS task, improved the coding schema of video analysis. During this post-activity discussion, the two participants from the pilot study were encouraged to reflect on their actions in relation to the coding schema proposed by the researchers. Forms of cooperative manipulation (Table 1) directly address RQ1, while emerging collaborative roles (Table 2) inform RQ2. Difficulties identified through inductive analysis contribute to answering RQ3.

In this analysis, codes M0-M8 were designated for different forms of cooperative manipulation (refer to Table 1), and codes C1-C7 were used to categorise emerging collaborative roles (refer to Table 2). Additionally, difficulties arising during pair interactions were identified through inductive analysis, highlighting four main challenges: competitive behaviour (D1), the absence of a leading figure (D2), lack of communication (D3), and misinterpretation of the task (D4).

To further understand participants' collaborative roles within their manipulative activities in the CreaCube task, their roles were delineated during three critical periods: (i) the first 30 s after initial contact with the cubes, (ii) the final 30 s before the completion of task 1, and (iii) the final 30 s before the completion of task 2 (illustrated in Fig. 1).

Two researchers independently coded a subset of the video data (two pairs), applying the developed coding framework for both cooperative manipulation forms and emerging collaborative roles. Discrepancies were discussed and resolved through consensus, leading to refinement of the coding schema. The remaining pairs were then coded by one researcher, with periodic checks by a second coder to maintain consistency.

The analytical framework allows us to move beyond a simple description of the interactions to a deeper analysis of the underlying collaborative dynamics, permitting us to answer our research questions on the manipulative cooperative forms of each pair of learners (RQ1), the emergence of collaborative roles (RQ2) and the collaborative difficulties encountered (RQ3).

To answer our first research question (RQ1), which examines the pairs' cooperative manipulation, we analyzed the frequencies and sequential patterns of codes related to each of the cooperative manipulation types (*Co-construction*, *Apparent co-construction*, *Divergent manipulation*, *Apparent divergent manipulation*, *Acquiescent co-elaboration*, *Apparent acquiescent co-elaboration*, *One-sided manipulation*, *apparent One-sided manipulation*, *Individual manipulation)*. The quantitative data from the coding grid showed the shift in the distribution of these pairs' cooperative manipulation over the course of the task, while the

Table 1 Adaptation of the basic forms of verbal Cooperation (Baker, 2002) to the forms of cooperative manipulation in creacube

Basic forms of verbal cooperation (Baker, 2002)	Forms of cooperative manipulation in CreaCube Framework - Description
Co-construction: The interaction is aligned and symmetrical, and the students agree.	*Co-construction (M1)*: The participants are working together (four hands) to build the artefact with a common goal in mind. Participants show a genuine understanding and agreement. [4 hands-team]
Apparent co-construction: The interaction is symmetrical and non-aligned, and the students agree.	*Apparent co-construction (M2)*: The participants manipulate the cubes towards the same objective (e.g., exploring the features), but the manipulation of the cubes takes place in parallel (the participants are not building one common artefact, but different ones). [4 hands-freestyle]
Co-argumentation: The interaction is aligned and symmetrical, but the students disagree.	*Divergent manipulation (M3)*: Participants manipulate the cubes together (4 hands) to achieve a common goal. They understand their partner's manipulations, but they disagree. [4 hands in disagreement]
Apparent co-argumentation: The interaction is symmetrical, non-aligned, and the students disagree.	*Apparent divergent manipulation (M4)*: Participants manipulate the cubes together (4 hands) towards a common objective, but they disagree and do not understand their partner's manipulations. [4 hands in disagreement and confusion]
Acquiescent co-elaboration: The interaction is asymmetrical and aligned. The students agree. Different roles (e.g., builder and leader)	*Acquiescent co-elaboration (M5)*: The participants take on different roles (e.g., hand, critic, etc.). They understand each other's ideas and proposals and agree. For example, when one participant proposes a certain figure of cubes, the other participant understands the reasons behind the proposal and agrees. [4 hands OR (2 hands + 2 eyes) in different roles]
Apparent acquiescent co-elaboration: The interaction is asymmetrical and non-aligned. The students agree.	*Apparent acquiescent co-elaboration (M6)*: The participants take different roles (e.g., hand, brain, etc.). Even though there is agreement, there is no genuine understanding. [4 hands OR (2 hands + 2 eyes) in different roles in confusion]
One-sided argumentation: When the interaction is asymmetrical and aligned with disagreement, it leads to argumentation.	*One-sided manipulation (M7)*: After a figure /solution has been completed, one participant expresses disagreement and manipulates the cubes to propose a new figure /solution. The other participant only observes and understands the new figure /solution proposed. [turn-taking]
Apparent one-sided argumentation: The interaction is asymmetrical, non-aligned with disagreement.	*Apparent one-sided manipulation (M8)*: After a figure /solution has been completed, one participant expresses disagreement and attempts (fails/succeeds) to manipulate the cubes without consent to propose a new figure /solution. The other participant only observes. [turn-taking without consent]
-	*Individual manipulation (M0)*: Only one participant manipulates the cubes. There is no collaboration. [only 2 hands]

qualitative analysis of the corresponding video segments provided contextual examples of how these roles were expressed and how participants negotiated them.

To answer RQ2, the analysis of emerging collaborative roles followed a two-step process. First, our coding grid included the students' roles (*Brain*, *Hand*, *Critic*, *Proposer*, *Risk Taker*, *Explorer*, *Follower).* We applied these codes to the video data during three critical time periods: the initial 30 s of Task 1, the final 30 s of Task 1, and the final 30 s of Task 2. This structured application of the grid allowed us to create a temporal map of role evolution within each pair. The data from the grids provided the evidence for our findings that roles were dynamic and that participants initially acted as Explorers before adopting more

Table 2 Emerging collaborative roles in creacube adapted from Cassone et al. (2021) and Chiu (2001)

	Emerging Collaborative Roles	Definition
R1	Brain	The brain reflects and proposes strategies, but it is more reticent to touch the cubes.
R2	Hand	The hand is a proactive person, usually not eager to let the other participant access the cubes until he/she realises that he/she is not able to succeed on his/her own.
R3	Critic	The critic shows flaws and suggests alternatives.
R4	Proposer	The proposer comes up with new ideas.
R5	Risk Taker	The risk-taker takes initiatives without consulting the partner.
R6	Explorer	The explorer explores resources' different possibilities and characteristics.
R7	Follower	The follower follows the instructions of his/her partner without any reflection or questioning.

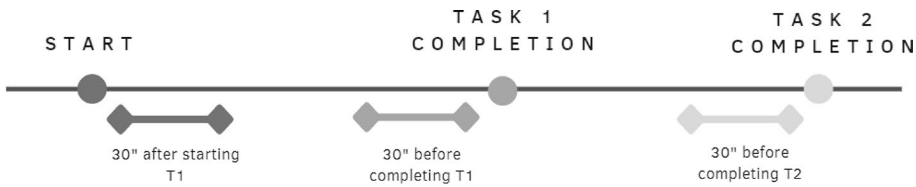

Fig. 1 Representation of the key time periods for the analysis of participants' emerging collaborative roles in CreaCube

defined roles like Proposers. We then leveraged the qualitative data from the video analysis to provide concrete examples, such as the Proposer/Critic dynamic in Pair 5 or the Brain/Hand partnership in Pair 6, which moved our findings beyond simple descriptive trends.

To answer RQ3, we used an inductive analysis approach to identify difficulties that arose during the interactions. We systematically reviewed the video footage to identify recurring challenges, which were then classified into four main categories: Competitive behavior (D1), Absence of a leading figure (D2), Lack of communication (D3), and Task misinterpretation (D4). The grid served as a tool to log the occurrence and context of these difficulties for each pair of learners, allowing us to provide evidence that these challenges negatively affected collaboration. The direct link between the grid and our findings is exemplified by how we used the logged data to identify specific instances, such as the competitive behavior observed in Pairs 3 and 6, the lack of communication in Pair 4, or the misinterpretation of tokens in Pairs 3 and 6. This direct link between our coded observations and our reported findings ensured that our conclusions about the difficulties were systematically grounded in the empirical data.

6 Results

This section presents the results according to each research question (RQ).

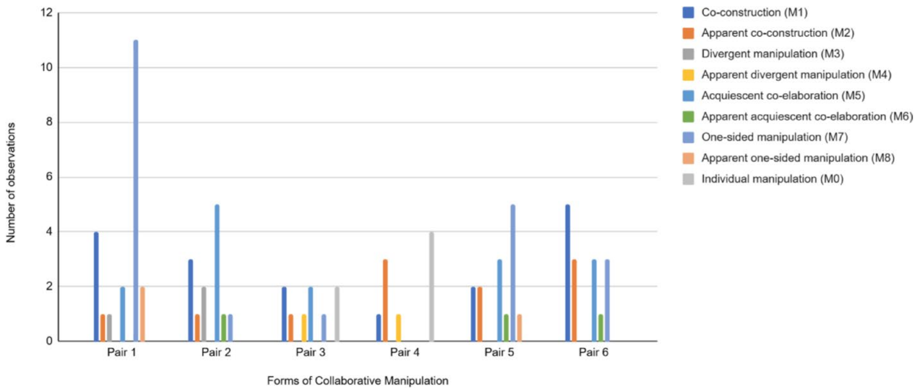

Fig. 2 Identification of pairs' cooperative manipulation forms

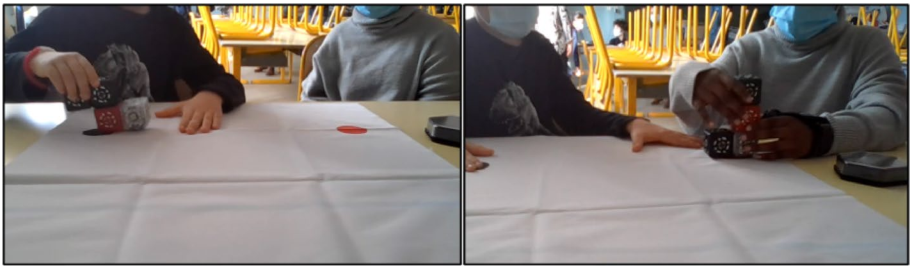

Fig. 3 Turn-taking (M7) in Pair 1

6.1 RQ1: Throughout the CreaCube activity, What Are the Pairs' Manipulative Cooperative forms?

The analysis of the pairs' CPS revealed that participants' interactions towards the CreaCube task solution differ substantially from pair to pair. Figure 2 presents the forms of collaborative manipulation that each pair of learners used to complete CreaCube tasks 1 and 2.

In the first pair, we observed that the participants primarily engaged in turn-taking (M7). Even though there were some periods of co-construction that enabled the participants to reach the solution to task 1, there was often disagreement between them that led them to take turns proposing the construction of new vehicle figures (Fig. 3).

Note In Pair 1, the interaction is mostly based on turn-taking (M7), in which the participants manipulate the cubes to propose a new figure /solution (Capture on the left 6:20, capture on the right 7:12).

On the contrary, the second pair was mostly involved in acquiescent co-elaboration; the participants adopted different collaborative roles, providing and receiving feedback on the cubes' features and position (Fig. 4). Despite some occasions of disagreement (M3) and misunderstanding (M6) in the most challenging parts of the task (e.g., the function of the red cube), there was good communication between the partners. This good communication

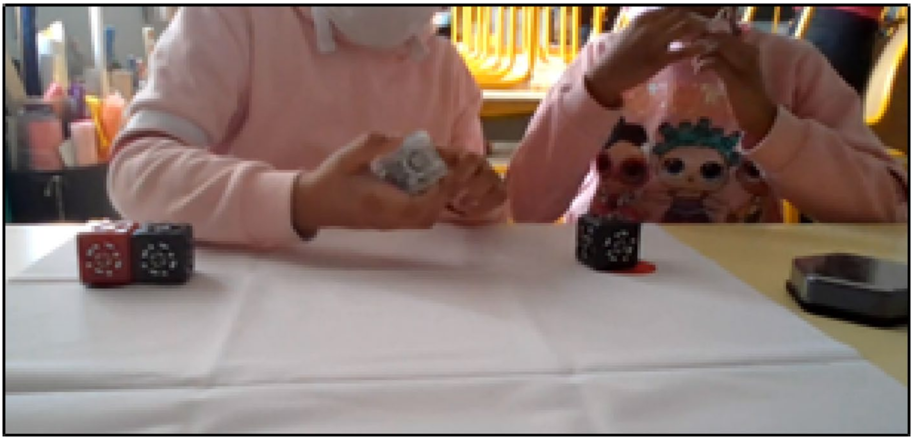

Fig. 4 Acquiescent co-elaboration in Pair 2

could possibly be because the participants were justifying their ideas and manipulations. For instance, participant A provided a rationale for her proposed orientation of the white cube, stating that the vehicle requires the wheels to be on the table to move. Similarly, participant B justified her manipulation of the black cube by emphasising its importance as the vehicle's light source.

Note Pair 2 participants were taking on different roles. In caption 2:13, participant A is showing participant B the white cube (motor) and explaining what the position of the cube should be.

Also, in the third pair's interaction, participant A dominated both tasks. Even though participant B offered ideas (M5), participant A dominated the task by moving the cubes on her own (M0), rejecting B's ideas (M4), making decisions without considering other points of view (M7), and acting in ways that were not cooperative (for example, pulling the cubes and putting too much emphasis on her own contribution). Even though there were some periods of co-construction (M1), they were short and not directly related to the task's resolution.

When the fourth pair worked together, they didn't talk to each other very much. At the start of task 1, both participants explored the cubes' features (M2) and made the first artefact together (M1), but participant B mostly manipulated the cubes by himself (M0) (Fig. 5). Unlike the third pair, participant A appeared disengaged from the task, as they did not offer any suggestions or take turns manipulating the cubes.

Note In Pair 4, participant A was not engaged in the activity. Participant B was mainly manipulating the cubes on his own (M0).

In the fifth pair, the participants demonstrated engagement and effective interaction throughout both tasks. Their interaction was characterised by turn-taking in proposing new figures (M7) and evaluating the partner's manipulations (M5). In general, there was good communication and understanding, apart from the following two instances that occurred in the first task: (i) participant B insisted on leaving the red token on the desk (M6) with A not under-

Fig. 5 Individual manipulation in Pair 4

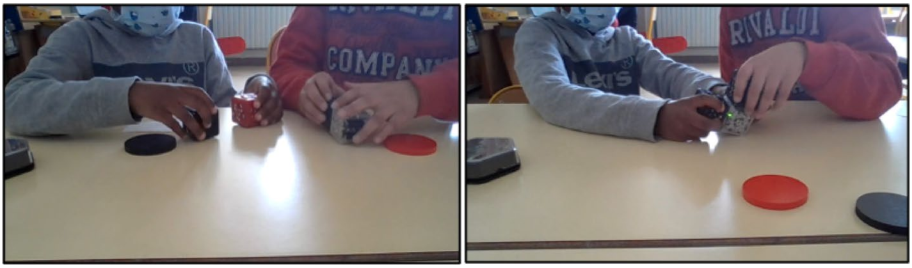

Fig. 6 Apparent- co-construction (M2) and co-construction (M1) in Pair 6

standing why but following his instructions; and (ii) participant B grabbed the red cube from A's hands to make a new figure (M8).

In terms of the sixth pair's interaction, the participants remained engaged and interacted effectively throughout both tasks. Several periods of co-construction (M1) and apparent co-construction (M2) were observed (Fig. 6). During the apparent co-construction periods, the participants were manipulating the cubes in parallel without building one common figure. For instance, at the start of task 1, both participants independently explored the cubes and their features without creating a shared feature. In task 1, there were some short turn-taking periods (M7) in which participant B proposed new figures. Participant A also provided feedback (M5) to the partner regarding the vehicle's function ("it needs to run on its own") and direction ("from the red to the back point").

Note In the picture on the left, the participants are exploring the cubes without building a common figure (M2). In the picture on the right, the participants are building a common figure (M1).

Figure 7 presents the pairs' final manipulation forms, just before completing tasks 1 and 2, to better understand the cooperative manipulation forms that helped to achieve the solution of CreaCube tasks 1 and 2. The results reveal that the participants engaged in co-construction on six occasions, ultimately reaching the solutionDuring co-construction, the participants actively constructed a figure while understanding and agreeing with each other's perspectives. In addition, on three occasions, the participants managed to find the solution after being involved in one-sided manipulation, during which a participant disagreed with the previous creation and manipulated the cubes to propose a new solution with the other participant's approval. Finally, we observed that the participants achieved the solution on three occasions without any collaboration. This occurred in Pairs 3 and 4. As previously explained, these two pairs encountered challenges in their collaboration; in Pair 3, participant A demonstrated dominance and competition, denying participant B the opportunity to manipulate the cubes, while in Pair 4, participant A did not engage in the tasks for unknown reasons.

6.2 RQ2: What Collaborative Roles Emerge Throughout the CreaCube activity?

The analysis showed that in the beginning of the first task (key period 1), most of the participants acted as explorers (Fig. 8); as it was participants' first contact with the cubes, most of them tried to get familiar with the cubes and their features. Only one participant persisted in acting as an explorer until the end of the first task (key period 8). Most participants took on the role of the proposer, suggesting new figures, among other collaborative roles. As far as the end of the second task is concerned (key period 3), most participants were proposers, while some took the role of the hand and critic (Fig. 8). Throughout both tasks and all three key time periods, some participants acted as followers, following their partners without questioning or reflecting. This is consistent with the findings from the previous section on collaborative manipulation forms; in Pairs 3 and 4, there were instances of individual manipulation in which one of the participants assumed the role of the follower.

Table 3 presents the results of the participants' roles in key time periods 1, 2, and 3 in more detail for each pair.

As shown in Table 3, the participants of Pair 1 immersed themselves in exploring the cubes' features at the beginning of task 1 (key period 1). Towards the end of task 1 (key

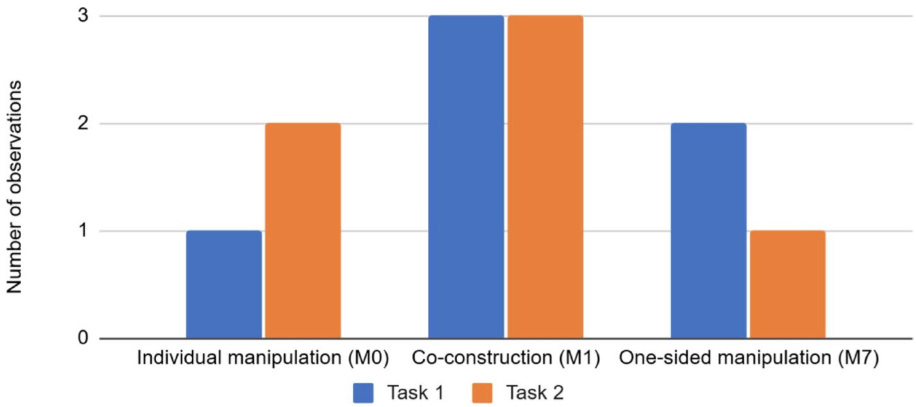

Fig. 7 The CreaCube activity is completed through various manipulations

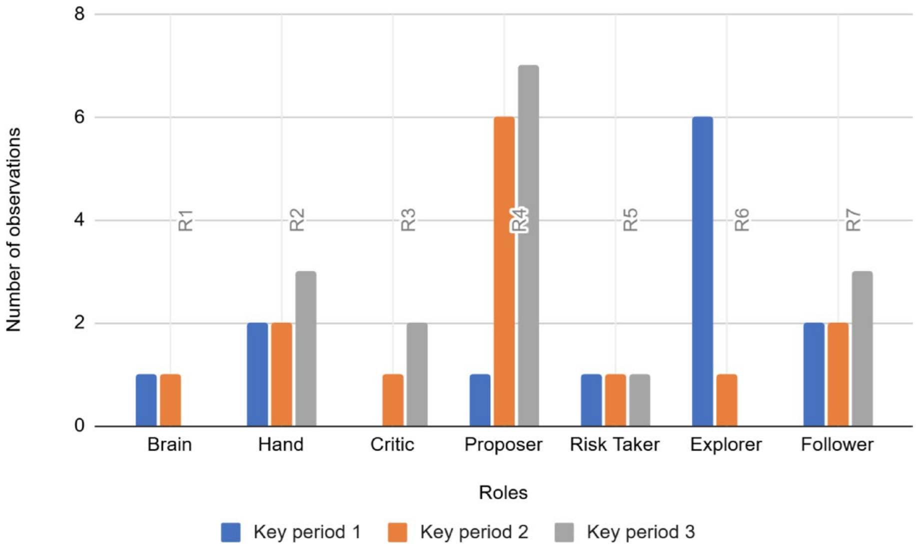

Fig. 8 Participants' roles in key time periods 1, 2, and 3

Table 3 The roles of participants in key time periods 1, 2, and 3

		Key period 1	Key period 2	Key period 3
Pair 1	Participant A (M)	Explorer	Risk-taker	Proposer
	Participant B (M)	Explorer	Explorer	Proposer
Pair 2	Participant A (F)	Follower	Proposer	Follower
	Participant B (F)	Proposer	Proposer	Proposer
Pair 3	Participant A (F)	Explorer	Hand/Proposer	Risk-taker/ Hand/Proposer
	Participant B (M)	Explorer	Follower	Follower
Pair 4	Participant A (F)	Follower	Follower	Follower
	Participant B (M)	Explorer	Proposer	Proposer
Pair 5	Participant A (M)	Explorer	Critic	Critic
	Participant B (M)	Hand	Proposer	Hand/Proposer
Pair 6	Participant A (M)	Brain	Brain	Critic
	Participant B (M)	Hand/Risk-taker	Hand/Proposer	Hand/Proposer

period 2), participant A demonstrated a risk-taking behaviour by telling the teacher that they had found the solution without consulting his partner first. At the end of task 1, participant B continues exploring and tries to figure out the cubes' features and instructions. At the end of task 2 (key period 3), both participants suggested different vehicle figures, acting as proposers. During the activity, participant A began to lose motivation, while participant B remained more engaged and focused.

Regarding Pair 2's collaborative roles, participant B was domineering and always acting as a proposer, whereas A tended to follow B's instructions even when she did not completely agree. In general, there was good communication between them because they both tended to justify the proposed solutions and their manipulations.

In Pair 3, participant A displayed domineering behaviour throughout both tasks (taking one-sided decisions, restricting B's access to the cubes, etc.). B showed a keen interest in the problem-solving process by actively exploring the cubes' features and providing suggestions at the beginning of task 1. However, A's competitive and domineering behaviour forced him to gradually participate less and become submissive. Even though participant A dominated the task, she communicated with B by providing explanations and justifying her manipulations, acting as B's teacher and tutor.

In Pair 4, neither of the participants was a leading figure; both were very hesitant to manipulate the cubes; it took participants A and B 40 and 20 s, respectively, to touch the first cube. In the absence of a leader, B took responsibility for the task and proposed several figures. Participant A appeared disengaged from the task; she did not offer any suggestions for B's figures and did not take turns manipulating the cubes. In contrast to Pair 3, the participants lacked communication; B remained silent and offered no explanations for his manipulations.

In Pair 5, participant B is the leading figure; through the task, he took on the roles of the 'hand' and the 'proposer', as he was proactive and suggested several ideas. Participant A was very attentive as he discovered the cubes' most important features (wheels, switch buttons). This personal trait enabled him to assume first the role of the explorer and then the role of the 'critic'. Participant A complemented B's proactive behaviour by providing his partner with feedback and suggesting improvements (e.g., the vehicle's balance).

Finally, in Pair 6, participant B acted as the 'hand', 'proposer', and even 'risk-taker' by being more active throughout the problem-solving process. On the contrary, participant A took a reflective role and acted more like the 'brain' and 'critic' throughout the process. Participant A tried to figure out the instructions of the task before starting to manipulate the cubes, while he provided his partner with feedback (M5) regarding the function of the vehicle: 'it needs to run on its own' and its orientation: 'from the red to the back point'. The difference between the two participants' ways of thinking was evident at the beginning of task 2, in which participant B grabbed the cubes and started building while participant B was holding one cube in his hand and exploring it.

Taking everything into consideration, the participants assumed different collaborative roles, which evolved over the course of the activity. Despite the unfolding of roles, the evolution among the pairs followed a similar pattern, with roles alternating within the task. The initial collaborative roles evolved into complementary ones that were not diametrically different. The evidence from the analysis of these pairs' interactions showed that the participant who first behaved as a leader remained the leading figure until the end of the activity.

6.3 RQ3: What Kind of Difficulties Did Participants Confront Throughout their Collaboration in the CreaCube activity?

Throughout the activity, the participants faced the following difficulties that negatively affected their collaboration: competitive behaviour (D1), absence of a leading figure (D2), lack of communication (D3), and misinterpretation of the task (D4). Figure 9 reports that these difficulties occurred.

(Figure. 10) First. we observed that the participants displayed competitive behaviour in 4 out of 6 pairs, (Pairs 1, 3, 5, and 6), (Fig. 10). In Pairs 3 and 6, the participants were competitive both verbally, ("I found the solution," "I told you so," "I found the solution to task 1, so I will work on task 2," "Thanks to me, we solved the task") and physically, (e.g., pulling the cubes). In Pair 3, participant A's competitive behaviour demotivated the partner and dete-

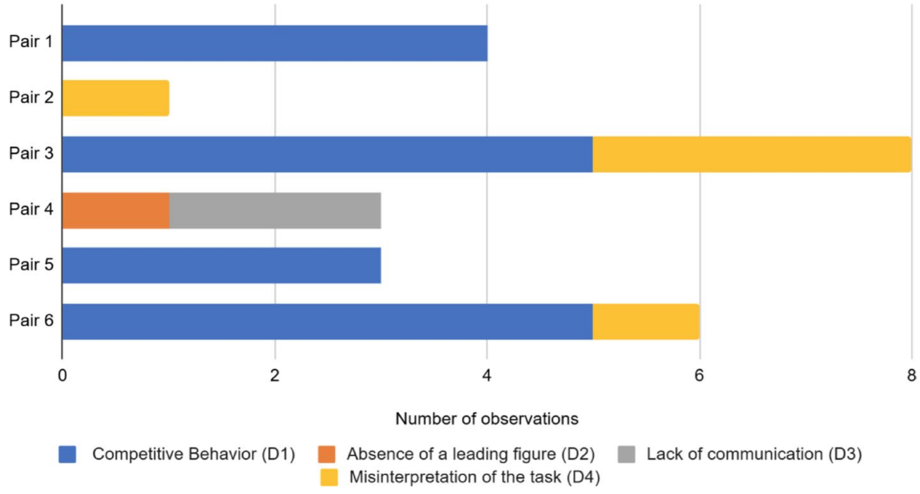

Fig. 9 Identification of difficulties in pairs' collaboration

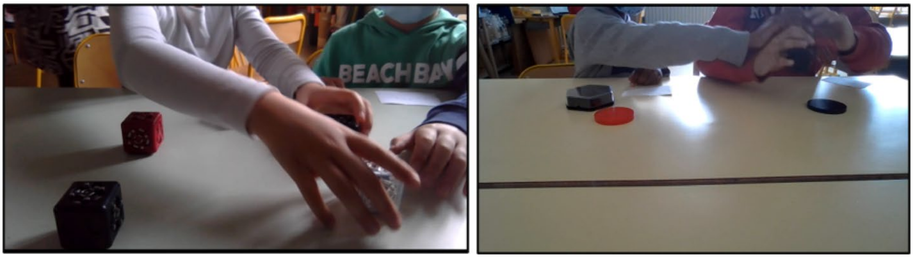

Fig. 10 Pairs 3 and 6 exhibit competitive behavior by pulling the cubes

riorated collaboration, while in Pair 6, it increased participants' stress to find the solution as fast as they could. It is important to point out that in Pair 2, (in which both participants were female) and in Pair 4, (in which participant A was reluctant to manipulate the cubes), there weren't any competitive behaviours.

Note Some participants dominated the activity, often pulling the cubes to make new figures.

When it comes to the absence of a leading figure (D2), in Pair 4, both participants seemed unwilling to manipulate the cubes at the beginning of the task (see Fig. 11). In Pair 4, there was also a lack of communication (D3) between partners during two long periods, the first one in task 1 and the second one in task 2, in which participant B manipulated the cubes without discussing his decisions with participant A. Ultimately, several pairs misunderstood certain aspects of the task (D4). Pair 3 and 6 misinterpreted the use of the red and black tokens as they were trying to attach them to the vehicle. Pair 6 almost reached the end of the first task, insisting on attaching the tokens to the vehicle (Fig. 11). At the start of task 1, Pair 2 misinterpreted the instructions and intended to create two separate vehicles.

Fig. 11 Pair 4 (D2) lacks a leading figure, *while Pair 6 misunderstands the instructions (D4)*

Table 4 Summary of main results according to research questions

Research Question	Findings	Key Examples / Observations
RQ1: Manipulative cooperative forms of the pair of learners	Three main forms identified: • Co-construction (most effective) • Acquiescent co-elaboration • One-sided manipulation	• Co-construction led to successful outcomes in six cases. • Pair 2: Strong co-elaboration with mutual feedback. • Pairs 3 and 4: Dominance or disengagement hindered collaboration.
RQ2: Emergence of collaborative roles	Dynamic and evolving roles observed: • Explorer, Proposer, Hand, Critic, Follower, Brain, Risk-taker	• Most participants began as explorers. • Pair 5: Complementary roles (Critic and Proposer). • Pair 6: Reflective (Brain) and active (Hand) partnership.
RQ3: Collaborative difficulties encountered	Four main difficulties identified: • Competitive behaviour • Lack of leadership • Communication gaps • Task misinterpretation	• Competitive dynamics in Pairs 1, 3, 5, and 6. • Pair 4: Absence of leader and limited interaction. • Pairs 3 and 6: Misuse of tokens due to misunderstanding.

Note *In Pair 4, both participants were hesitant to manipulate the cubes (picture on the left), while in Pair 6, participants mistakenly attached the tokens to the vehicle.*

6.4 Summary of Findings

After detailing the findings for each research question, Table 4 presents a summary of the main results.

7 Discussion

This study examines how six pairs engaged in CPS interact with modular robotics in a dynamic, unstructured activity. This analysis revealed that there is no single cooperative strategy for solving the CreaCube activity, but rather a variety of strategies, each composed of different cooperative manipulation forms, that can lead to the completion of the activity. In the same vein, the emerging collaborative roles assumed by the participants in every pair were quite different from one pair to the next. Strijbos and Weinberger (2010) explain the diversity in the roles assumed throughout ill-structured activities, supporting the idea that the roles emerging in CSCL closely relate to participants' personal skills. Therefore, as participants have different personal traits and skills, it is reasonable that they will adopt different collaborative roles in the activity. Despite the diversity in participants' roles, there were some common points in the roles that emerged over the course of the activity; in pairs' first contact with the cubes, the most common role emerged was that of the 'explorer', while towards the end of the first and second tasks, most of the participants behaved as 'proposers'. The assumed roles align with the essence of the proposed task, which requires first exploring the cubes' characteristics to build a solution. Our analysis revealed that the most successful pairs navigated the problem-solving process by fluently transitioning between emergent roles and cooperative forms that supported each stage of the cycle. During problem definition, roles such as Proposer (R1) and Critic (R2) were essential as they used Acquiescent co-elaboration (M2) to establish a shared understanding of the CreaCube task. This collaborative foundation allowed them to transition effectively into the solution generation phase, where they engaged in Mutual co-construction (M3) to develop a joint plan. In contrast, pairs who struggled often demonstrated Individual manipulation (M0) during the implementation stage, a behavior that bypassed both solution generation and evaluation, ultimately leading to less favorable outcomes and highlighting a breakdown in the cooperative process.

Furthermore, the study of participants' emerging collaborative roles revealed that some participants had a passive attitude, assuming the role of the follower in some parts of the task (Pair 2, participant A, and Pair 3, participant B) or throughout the whole course of the activity (Pair 4, participant A). Cassone et al. (2021) have previously observed and documented submissive and domineering behaviours in collaboration during the CreaCube activity.

This study backs up what was already known about dominant behaviours in CreaCube and shows that when two people play together, they show individualistic and competitive behaviours, both verbally and physically. Instead of showing cooperative behaviour to collectively reach a solution, some participants pursue their own solution to the task at an individual level. As reported by Popov et al. (2019), "individualists are more likely to exhibit competitive behaviour focused on personal achievement" (p. 103). For instance, some pupils insisted on being the ones to lead the pair to the solution of the activity, and as Cassone et al. (2021) reported, some pupils seemed to be disappointed in not being the ones who led the pair to success. Some pupils, when engaged in the CreaCube task, do not perceive the task as a cooperative learning situation but rather as a competitive and individualistic situation; according to Johnson et al. (1986), "in a competitive learning situation, when one student achieves their goal, all others with whom they are competitively linked fail to achieve their goals, and in an individualistic learning situation, students' goal achievements are independent" (p. 383). Therefore, cooperative learning is not always present in CPS activities. Participants' unfamiliarity with collaborative tasks and unstructured CPS activities could explain this. While this exploratory study's scope and sample size limit its broad generalizability, this micro-analytic analysis (Palincsar, 2012) was essential for a fine-grained understanding of how collaborative roles and interaction patterns emerge and evolve during a CPS robotic activity, a key contribution that provides a foundational model for future, larger-scale research.

The gender composition of the pair is another aspect that requires further study. The study's results demonstrated that in same-gender pairs, a lot of competition occurs when the participants are male (Pairs 1, 5, and 6), but no competition occurs when all participants are female (Pair 2). When it comes to the mixed gender pairs (Pairs 3 and 4), the two cases in the sample are contradictory; in Pair 3, there was a very dominant female participant, while in pair 4, the female was unwilling to actively participate in the task. Given the limited sample size, we need to conduct additional research on the gender composition of pairs in CPS to obtain reliable results on potential gender differences in manipulation processes and emerging collaborative roles. Previous studies in this area have found interesting but sometimes conflicting results. For example, Holmes-Lonergan's study (2024) on traditional gender stereotyped behaviours found that preschool girls use mitigation more frequently than boys when engaged in problem-solving tasks, and that girls in same-gender pairs are more likely to agree with each other than boys. On the contrary, Tomai et al. (2014) found that computer-supported collaborative learning (CSCL) promotes counter-stereotypical gender communication styles in male and female university students, with males exhibiting more social-emotional communication styles and females showing task-oriented communication styles.

The observed prevalence of competitive behaviors suggests that educators should scaffold CPS activities by assigning flexible but predefined roles. Such scaffolding can help balance participation and foster positive interdependence. Based on our finding that pairs with complementary and balanced roles showed better coordination and outcomes, we also propose a structured pedagogical intervention. Teachers could implement a short pre-task role-definition exercise to mitigate competitive behavior and the lack of a leading figure. This would involve introducing and having students explicitly assign themselves roles like Proposer, Critic, Hand, and Follower before starting a task. The intervention would also include a mandatory role rotation, ensuring both partners experience different functions, thereby fostering more equitable and effective collaboration.

This study provides a multimodal framework for analyzing CPS in modular robotics tasks, highlighting the importance of co-construction and balanced role distribution. Future studies should investigate scalable scaffolding strategies and explore gender-related dynamics in larger samples. Additionally, investigating the impact of predefined role assignments on collaboration effectiveness could provide further insights.

Declarations

Ethical Approval All procedures performed in studies involving human participants were in accordance with the Ethical Committee of Université Côte d'Azur (CER2019-6).

Consent to Participate Informed consent was obtained from all individual participants included in the study.

Conflit of Interests No conflicts of interest to disclose.

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