

Article

A Child–Robot Interaction Framework for Designing Inclusive Educational Robotics in Resourced Classrooms: (Robo-ICARE)

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Abstract

This study presents Robo-ICARE (Robotics-Inclusive Child-Centered Approach for Robotics in Education), a Child–Robot Interaction (cHRI) framework for designing inclusive educational robotics in under-resourced and multigrade classroom contexts. The framework addresses gaps in existing educational robotics approaches by integrating user-centered design, affective expressiveness, pedagogical alignment and inclusivity, with particular attention to learner variability and contextual constraints. Robo-ICARE comprises six inter-related design dimensions—embodiment, interactivity, intelligence, pedagogical alignment, inclusivity, and user-centered process—intended to guide the design implementation, and evaluation of educational robots in authentic classroom environments. The framework is operationalized and empirically examined through a case study involving COODI, a low-cost and emotionally expressive educational robot co-designed with students and teachers in rural Chile. The study follows a primarily qualitative, exploratory design-based research approach, supported by descriptive quantitative measures. Empirical evaluation with 49 participants focuses on usability, user experience, engagement, and emotional acceptance, rather than on causal measurement of learning gains. The findings indicate that the proposed framework supports the design of emotionally engaging and context-sensitive educational robotics experiences that are feasible in low-resource settings. Overall, this work contributes a design-guiding, empirically grounded framework that bridges child–robot interaction theory and educational practice, offering a replicable approach for inclusive educational robotics in under-resourced classroom contexts.

Keywords: child–robot interaction; educational robotics; education; educational technology; user-centered design; STEM education



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1. Introduction

The integration of robotics in education has emerged as a promising strategy to engage students in STEM (Science, Technology, Engineering, and Mathematics) learning [1–3]. Educational robotics has been shown to foster problem-solving, creativity, and hands-on exploration, aligning with constructivist [4] and constructionist learning theories [5,6]

that emphasize learning through making, experimentation, and reflection [5,7]. Recent systematic reviews and empirical studies further confirm that robotics-based learning can support the development of computational thinking, collaboration, and motivation across different educational levels, from primary education to higher education [1,8].

However, accumulating evidence suggests that the educational effectiveness of robotics is not determined solely by technological capabilities. Rather, it depends critically on how robotic systems are pedagogically aligned with learners' developmental characteristics, classroom practices, and contextual constraints [9]. This dependency becomes particularly salient in rural and under-resourced schools, where limited infrastructure, insufficient teacher training, and challenges in curricular integration often undermine the sustainability and long-term impact of robotics initiatives [10].

Educational robotics spans a wide spectrum, from introductory STEM activities to advanced research in mechanical design, embedded systems, artificial intelligence, and human–robot interaction (HRI) [11]. Despite this technological breadth, a persistent gap remains between the potential of robotic technologies and the availability of pedagogically grounded, context-sensitive design frameworks capable of supporting inclusive learning across diverse educational environments. In many cases, robotics initiatives prioritize technical sophistication over educational coherence, resulting in solutions that are difficult to implement or sustain in low-resource classroom contexts.

Within this landscape, social robots have gained increasing attention in educational settings [12], where they may function as tutors, peers, or learning companions [13,14]. Prior work has classified social robots as educational tools based on their capacity to interact with people and environments in pedagogical contexts [15,16], and has identified a wide range of programming paradigms—from block-based coding to tangible and demonstration-based approaches—that support adaptable learning experiences. While these contributions highlight the versatility of educational robots, they primarily describe interaction modalities rather than offering integrative guidance on how robots should be designed to support inclusive, emotionally engaging learning in real classrooms.

Child–Robot Interaction (cHRI), a subfield of HRI, provides a theoretical lens of examining how children engage with robots to support cognitive, emotional, and social development [17,18]. Research in cHRI has demonstrated that embodied and emotionally expressive interaction can foster motivation, collaboration, and curiosity through multimodal non-verbal communication [19]. Nevertheless, most cHRI-driven educational robots are developed and evaluated in laboratory settings or well-resourced urban schools, leaving the specific needs of rural and under-resourced educational environments largely unaddressed [20].

To bridge this gap, several frameworks have been proposed to guide the design and implementation of educational robotics. For example, González-Oliveras et al. [21] identify four key design dimensions—embodiment, interactivity, intelligence, and educational purpose—highlighting the importance of moving beyond purely technical considerations. Similarly, Cano et al. [22] propose a design approach focused on emotional expressiveness through non-verbal communication modalities, demonstrating its impact on user engagement and emotional perception. While these contributions offer valuable insights, they tend to address design dimensions in isolation and do not fully integrate pedagogical alignment, inclusivity, and participatory design within a unified, design-guiding framework grounded in authentic classroom practice.

Taken together, existing work reveals a recurring limitation: although embodiment, interaction, and emotional expressiveness are widely recognized as important, they are rarely conceptualized as interdependent components of an inclusive educational robotics framework. In particular, there remains a lack of empirically grounded frameworks that si-

multaneously integrate child–robot interaction, affective expressiveness, inclusivity, design principles [23], and user-centered design [24], especially in under-resourced and multi-grade educational contexts. Addressing this limitation requires a framework that explicitly bridges technical, pedagogical, and affective dimensions while remaining feasible within real-world classroom constraints.

In response to this need, this article introduces Robo-ICARE (Robotics-Inclusive Child-Centered Approach for Robotics in Education), a design framework structured around six interrelated dimensions: (1) Embodiment, (2) interactivity, (3) Intelligence, (4) Pedagogical Alignment, (5) Inclusivity, and (6) User-Centered Process [24]. These dimensions are intended to guide the design, implementation, and evaluation of educational robots in authentic classroom settings, with particular attention to learner diversity and contextual limitations.

The framework is operationalized and examined through a real-world case study involving COODI, a low-cost and emotionally expressive educational robot. Importantly, COODI is not presented as the primary contribution of this work, but as an empirical instantiation used to validate the Robo-ICARE framework in rural school contexts. Rather than measuring causal learning gains, the study focuses on usability, engagement, and emotional acceptance as experiential indicators for assessing the feasibility and relevance of the proposed framework in practice.

Accordingly, this study contributes to the field of educational robotics and cHRI by the following:

- (i) Proposing an evidence-based design framework that integrates technical, emotional, and pedagogical dimensions.
- (ii) Demonstrating its application through participatory design and classroom implementation in under-resourced schools.
- (iii) Providing empirical evidence related to usability, engagement, and emotional acceptance among students and teachers.

The remainder of this article is structured as follows. Section 2 presents the theoretical background, including educational robotics, child–robot interaction, user-centered design, and emotional expressiveness. Section 3 describes the methodology, encompassing contextual analysis, framework operationalization, and evaluation procedures. Section 4 reports the results, while Section 5 discusses implications, limitations, and directions for future research. Finally, Section 6 concludes the article with final reflections and recommendations.

2. Theoretical Background

Educational robotics integrates programmable and often physically embodied technologies to enhance STEM learning, problem-solving, and computational thinking [8]. Rooted in constructivist and constructionist paradigms [5,7], these tools provide students with opportunities to design, experiment, and reflect through active engagement with technology. When robots are designed with both technical and pedagogical coherence, they can bridge cognitive and emotional learning processes [25], transforming abstract STEM concepts into tangible, meaningful experiences.

However, despite the growing body of research in educational robotics, much of the existing work remains fragmented, addressing isolated dimensions such as technical functionality, cost efficiency, or curricular alignment. Many studies prioritize either cognitive learning outcomes or technological feasibility, while insufficiently considering affective interaction, child-centered design [24], and inclusivity as integrated design requirements. This limitation is particularly evident in under-resourced and multigrade educational contexts [10], where learner variability, emotional engagement, and contextual constraint play a critical role in shaping meaningful learning experiences.

As a result, there is a lack of comprehensive, design-guiding frameworks that systematically integrate pedagogical, affective, and interactional dimensions within real classroom practice. This gap motivates the need for a framework that goes beyond descriptive classifications and technical guidelines, and instead supports inclusive, emotionally expressive, and context-sensitive educational robotics design.

2.1. Child–Robot Interaction (cHRI)

Child–Robot Interaction (cHRI) is a subfield of Human–robot Interaction that explores how children communicate, learn and develop socially and emotionally through their interactions with robots [17]. Robots in cHRI contexts act as peer, tutors, or learning companions, promoting engagement and empathy through embodied, affective, and multimodal communication [19,26].

Children often anthropomorphize robots, forming emotional bonds and attributing human-like traits [25]. When designed with affective and social dimensions in mind, robots can enhance motivation, attention, and engagement [27]. Key features of effective cHRI systems include embodiment, nonverbal communication, adaptability, and emotional expressivity [19,28–30]. As demonstrated by Löffler et al. [19], expressive cues such as color, motion, and sound are effective means of communicating emotional states in non-anthropomorphic robots. When combined with learning-oriented interaction, these expressive modalities can foster curiosity, empathy and collaboration core outcomes in child-centered education [31].

Despite this potential, most educational robots are designed in technologically rich environments, leaving rural or under-resourced classrooms underserved [10]. These contexts require simpler, low-cost, and adaptable designs capable of functioning offline, while still maintaining affective and social relevance. To address this challenge, this study introduces a framework for inclusive educational robotics design derived from both theory and empirical insights from real-world cHRI implementations.

2.2. From Design Dimensions to Framework Components

González-Oliveras et al. [21] propose classification framework for educational robots based on dimensions such as embodiment, interactivity, intelligence and educational purpose. One notable contribution in this line is the Low-Cost Educational Robotics (LCER) design framework [32], which emphasizes accessibility, affordability, and maintainability as central criteria for robotics implementation in K-12 education. LCER provides practical guidelines for hardware, software, and curricular integration, highlighting open-hardware and open-source development, modular construction, and teacher-friendly documentation to support sustainability in resource-limited schools. However, despite its strengths, this framework does not explicitly address affective, social, or interactional dimensions, which are critical for long-term engagement and inclusion—particularly in educational contexts where emotional connection, collaboration, and contextual adaptation play a key pedagogical role.

Complementary perspectives have also been proposed in the literature. For instance, a sustainable framework for autonomous robotics learning environments is presented in [33], which conceptualizes educational robotics through three core constructs: (1) the Participant (P), including teachers, learners, builders and experimenters; (2) the Environment (E), composed of computers, software, robots and physical material; and (3) the Arena (A), which represents application contexts such as competitive robotics, soccer robots, search-and-rescue scenarios, and other problem-based challenges. This framework contributes a systemic view of robotics education and emphasizes sustainability and application-driven

learning, but it remains largely focused on structural and organizational components rather than on children's emotional experience or inclusive interaction design.

Similarly, Alam et al. [4] introduced the Integrated Constructive Robotics in Education (ICRE) model, which aims to transform educational practices by embedding robotics into pedagogical settings. The ICRE framework incorporates dimensions such as pedagogical support and training, technological integration, community engagement, assessment, and inclusivity. While this model provides a broad educational and institutional perspective, it does not explicitly foreground child–robot interaction, emotional expressiveness, or the iterative co-design process with learners as central design principles.

Despite the growing number of frameworks and models proposed in educational robotics, several recurring limitations can be identified across the literature. First, many approaches address key dimensions such as embodiment, interaction, intelligence, or pedagogy in isolation, without articulating how these elements interact within real educational practices. As a result, design decisions are often fragmented and difficult to translate into coherent classroom implementations.

Second, affective and emotional expressiveness—when considered at all—is frequently treated as an interface-level enhancement rather than as a pedagogical mediator that actively supports engagement, motivation, and social interaction. This limits the explanatory and practical value of such approaches, particularly in child–robot interaction contexts where emotional engagement plays a central role.

Third, a significant proportion of existing frameworks are derived from laboratory-based studies or technologically rich environments, offering limited guidance for under-resourced or multigrade classrooms. Issues such as offline operation, teacher mediation, heterogeneous learner needs, and infrastructural constraints are often underexplored, reducing the applicability of these frameworks in real-world educational settings.

Finally, many prior contributions function primarily as descriptive taxonomies or high-level classifications, rather than as process-oriented frameworks that support iterative design, participatory development, and empirical validation in authentic classrooms. These limitations highlight the need for a framework that not only integrates technical, pedagogical, and affective dimensions, but also provides actionable guidance grounded in real educational contexts.

To bridge this gap, the present study introduces the Robo-ICARE framework (Robotics-Inclusive Child-Centered Approach for Robotics in Education), a framework for inclusive educational robotics grounded in child–robot interaction (cHRI). Unlike LCER, sustainable robotics environments, or integrative pedagogical models such as ICRE, Robo-ICARE places the child's embodied, emotional, and social interaction with the robot at the core of the design process. Rather than offering a static classification or high-level educational structure, Robo-ICARE adopts a process-oriented and empirically grounded approach, derived from participatory co-design, iterative prototyping, and classroom-based validation in under-resourced educational contexts.

A key novel contribution of Robo-ICARE lies in this explicit integration of affective expressiveness, pedagogical alignment, inclusivity, and user-centered design as first-class framework dimensions. Emotional expressiveness is treated not merely as an interface feature but as a mechanism for fostering motivation empathy, and sustained engagement. Inclusivity is addressed through principles aligned with Universal Design for Learning (UDL), enabling the framework to respond to heterogeneous classrooms, including rural and multigrade settings. Furthermore, Robo-ICARE conceptualizes intelligence as a pedagogically meaningful continuum, ranging from rule-based autonomy suitable for low-resource, offline environments to future adaptive and data-driven behaviors.

Overall, Robo-ICARE extends prior frameworks by moving beyond cost-driven structural, or institutional perspective toward a child-centered, affective, and design-guiding framework that explicitly connects technical design, pedagogical intent, and real-world classroom practice. As summarized in Table 1, while previous approaches have addressed sustainability, pedagogical integration, or social collaboration in isolation, Robo-ICARE uniquely integrates child-centered interaction, emotional expressiveness, inclusivity, and participatory design within an empirically grounded and process-oriented framework.

Table 1. Comparison of Robo-ICARE frameworks with existing works.

	Primary Focus	cHRI	Emotional/ Affective Design	Collaborative/ Social Skills	Data-Driven Learning Analytics	Adaptive AI/ Intelligence
[32]	Low-cost, sustainable robotics.	No	No	No	No	No
[33]	Structural sustainability.	No	No	No	No	No
[4]	Integrative pedagogical model.	Implicit	Limited	Moderate	No	No
[34]	Collaboration and social learning.	Yes	Moderate	Yes	No	No
[35]	Social robotics & analytics.	Yes	Yes	Yes	Yes	Moderate
Robo-ICARE	Inclusive, child-centered educational robotics	Yes	Yes	Yes	Moderate	Yes

Based on the identified gaps in existing frameworks and grounded in empirical classroom evidence the Robo-ICARE framework is structured around six interrelated design dimensions. These dimensions operationalize inclusive educational robotics from a child–robot interaction perspective, integrating technical, pedagogical, affective, and contextual considerations. Table 2 summarizes the dimensions of the Inclusive Educational Robotics Design Framework.

2.3. User eXperience on Child Robot Interaction

The concept of UX in cHRI extends beyond usability and functionality to encompass the child’s emotional, cognitive, and social engagement with the robot. In educational contexts, UX is crucial for ensuring that interactions are not only technically efficient but also affectively meaningful, fostering motivation, curiosity, and sustained attention [14]. Several studies have shown that positive UX outcomes in CRI are strongly linked to the robot’s design attributes, such as its expressivity, responsiveness, and role within learning tasks.

On the other hand, evaluating UX in children presents unique methodological challenges. Unlike adult users, children’s perceptions and affective responses are highly dynamic and context-dependent, influenced by their developmental stage, social environment, and familiarity with technology [37]. Therefore, assessing UX in cHRI requires age-appropriate instruments and multimodal evaluation methods, combining observation, self-reports using visual or simplified scales, and behavioral indicators of engagement. These approaches enable researchers to capture a more holistic understanding of children’s experiences, ensuring that the emotional and social dimensions of interaction are accurately represented alongside usability metrics.

Table 2. Dimensions of the Robo-ICARE framework and their design focuses.

Dimension	Analytical Design Focus
Embodiment	Examines how the robot’s physical form, size, and material presence shape children’s perception, emotional engagement, and approachability in educational contexts. This dimension considers expressivity through movements, color, and sound as mediating elements of interaction rather than as purely aesthetic features.
Interactivity	Addresses the nature and quality of interaction between children and robots, including communication modalities (visual, auditory, tactile) and interaction styles (reactive or proactive). The focus is on how interaction design supports engagement, turn-taking and sustained participation.
Intelligence	Conceptualizes intelligence as a pedagogically meaningful continuum, ranging from rule-based autonomy to more adaptive behaviors. This dimension examines how levels of autonomy and decision-making support learning activities without exceeding contextual or infrastructural constraints.
Pedagogical Alignment	Analyses the coherence between robot functionalities and educational objectives, ensuring alignment with STEM and introductory AI competencies, age-appropriate complexity, and curricular relevance within authentic classroom practices.
Inclusivity	Focuses on accessibility, equity Ensures accessibility, equity, and learner diversity, drawing on Universal Design for Learning (UDL) principles [36]. This dimension examines how design choices support participation across heterogeneous groups, including differences in age, ability, gender and learning pace.
User-Centered Process	Examines the extent to which teachers and students are actively involved throughout the design lifecycle, including contextual inquiry, co-design, prototyping, and evaluation. This dimension emphasizes participatory processes as mechanism for contextual relevance and sustainability.

Emotional expressiveness plays a central role in cHRI, influencing how children engage with educational robots and form meaningful connections. Expressive robots—those capable of displaying emotion through movement, light, sound, or facial animation—can foster empathy, trust, and motivation in learning context [19,38]. Ref. [19] tested combinations of color, motion, and sound to express basic emotions on a non-anthropomorphic robot. They found that combining color with planar emotion offered the best cost–benefit ratio in emotional communication. Specifically, joy was best conveyed through color and motion, sadness through sound, fear via motion, and anger via color.

3. Methodology

This study adopts a primarily qualitative, exploratory design-based research (DBR) approach [39], with the Robo-ICARE framework for designing inclusive educational robotics as the main object of investigation. DBR is particularly suited to studies aimed at developing and validating design frameworks within authentic educational settings, as it enables iterative refinement of theoretical constructs through empirical observation rather than statistical generalization or hypothesis testing. Quantitative instruments are therefore employed in a complementary and descriptive manner, providing formative indicators of usability, user experience, and engagement to support the qualitative analysis.

The methodological approach extends beyond technical prototyping to emphasize on the design and examination of emotionally engaging and pedagogically meaningful learning experiences situated in rural, multigrade educational contexts. In accordance with User-Centered Design (UCD) principles [24], the research process was participatory and iterative, involving teachers and students throughout the stages of co-design, classroom implementation, and formative evaluation. Educational activities were informed by

constructivist and constructionist learning theories [5,7] and structured around foundational STEM and introductory AI-related concepts, with particular emphasis on creativity, collaboration, and emotional expressiveness as mediating elements of learning.

Importantly, the educational robot used in this study functions as an empirical instantiation to operationalize and examine the Robo-ICARE framework, rather than as the primary research contribution. Methodological decisions were therefore guided by the need to assess how the framework's design dimensions manifest in practice, rather than to optimize or benchmark a specific technological artifact.

The study involved minimal risk educational activities and did not include the collection of identifiable personal data or images of participating children. All data were anonymized and reported in aggregate form, and parental authorization procedures were followed in accordance with the institutional guidelines of each participating school.

3.1. Research Design

The research process was organized into three analytically distinct but interrelated phases, each contributing to the validation of specific framework dimensions and to the progressive consolidation of the overall design model.

1. Exploratory phase

The exploratory phase focused on establishing the contextual and pedagogical foundations of the framework. Field observations and semi-structured interviews with teachers and students in rural multigrade and public schools were conducted to identify infrastructural constraints, pedagogical practices, and emotional expectations associated with educational robotics. Rather than serving as a requirements analysis for a specific technological artifact, this phase informed the contextual parameters and assumptions underlying the Robo-ICARE framework, particularly those related to inclusivity, pedagogical alignment, and emotional engagement.

2. Development phase—Co-Design and Operationalization

The development phase aimed to translate the conceptual dimensions of Robo-ICARE into empirically examinable design principles. Teachers and students participated in participatory co-design activities that supported the operationalization of framework dimensions such as embodiment, interactivity, intelligence, pedagogical alignment, inclusivity, and user-centered design. Iterative cycles of ideation, prototyping, and formative testing were used not to optimize a final product, but to examine how the framework's dimensions could be coherently instantiated in practice.

3. Validation phase

The validation phase examined the applicability and experiential impact of the Robo-ICARE framework through its implementation in structured STEM and introductory AI-related classroom activities. Quantitative instruments—namely the System Usability Scale (SUS) [40], and the User Experience Questionnaire (UEQ) [41]—were combined with qualitative data (interviews, classroom observations, and field notes) to support a triangulated, formative evaluation. The purpose of this phase was not to measure causal learning outcomes, but to assess usability, engagement, and emotional acceptance as indicators of framework feasibility and design coherence. Findings from this phase informed the final refinement of the framework and its associated design guidelines.

3.2. Framework Development Stages

The Robo-ICARE framework evolved through six iterative stages (Figure 1), reflecting a progression from contextual analysis to empirical validation and dissemination. These stages represent a process-oriented operationalization of the framework rather than a linear

project workflow, and each stage is analytically linked to one or more of the framework's core dimensions.

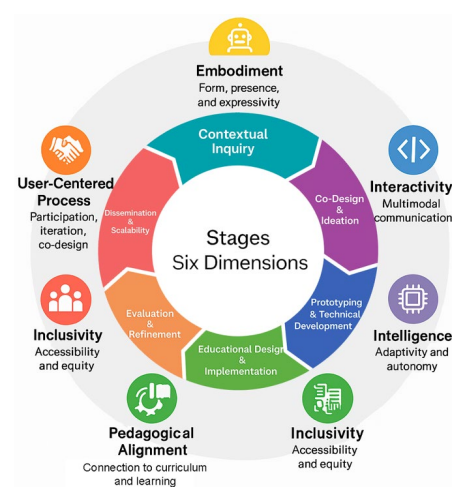


Figure 1. Robo-ICARE: framework for designing inclusive educational robotics from child–robot interaction.

Figure 1 illustrates the conceptual structure of the Robo-ICARE framework and its iterative development logic, while Table 3 summarizes the purpose, key activities, and primary framework dimensions addressed at each stage. Together, these elements clarify how the framework integrates technical, pedagogical, affective, and user-centered considerations across the research process.

Table 3. Frameworks stages proposed.

Stage	Purpose	Methodological Focus	Primary Framework Dimensions Addressed
Contextual Inquiry	Establish contextual, pedagogical and affective parameters for inclusive educational robotics design.	Classroom observations and semi-structured interviews used to identify infrastructural constraints, pedagogical practices, and emotional expectations in under-resourced and multigrade settings.	Embodiment, inclusivity, pedagogical alignment.
Co-Design & Ideation	Translate insights into design principles aligned with child–robot interaction.	Participatory design activities with teachers and students to explore embodiment, interaction styles, and emotional expressiveness as mediating elements of learning.	Embodiment, interactivity, user centered design.
Operationalization and prototyping	Operationalize framework dimensions through an empirical instantiation for analytical examination.	Iterative prototyping and formative testing used to examine how framework dimensions can be coherently instantiated in practice, rather than to optimize a final product.	Interactivity, intelligence, user centered design.

Table 3. Cont.

Stage	Purpose	Methodological Focus	Primary Framework Dimensions Addressed
Educational design and implementation	Examine pedagogical alignment and inclusivity during authentic classroom use.	Design and implementation of structured STEM and introductory AI-related activities to observe how the framework supports engagement, collaboration, and curricular coherence.	Pedagogical alignment, inclusivity.
Evaluation and refinement	Assess experiential indicators of framework feasibility and coherence.	Triangulation of quantitative (SUS, UEQ) and qualitative data (observations, interviews, reflection logs) to evaluate usability engagement, and emotional acceptance.	All six dimensions
Dissemination and Scalability	Examine the framework's transferability and sustainability beyond the pilot context.	Open-access documentation, teacher training activities, and external validation to assess adaptability across different educational environments.	Inclusivity, user-centered process.

Each stage generated feedback loops among designers, educators, and learners allowing continuous refinement of both the prototype and the framework's theoretical model.

By structuring the framework development in this way, Robot-ICARE moves beyond descriptive classifications of educational robots and instead provides a design-guiding and empirically grounded model that can be adapted and replicated across under-resourced educational contexts.

3.3. Participants and Context

Empirical validation of the framework was conducted in two complementary contexts to ensure ecological validity and scalability across diverse schools' environments.

1. Primary Context—Petorca Rural multigrade School (pilot implementation):

The initial design and implementation took place at *Escuela Juan Pablo II* in Petorca, Chile a public rural multigrade school characterized by limited digital infrastructure and heterogeneous age groups within the same classroom.

- Students: 14 participants (9 boys, 5 girls), aged 9–14 years, enrolled in grades 6–8.
- Teachers: 2 co-design collaborators who participated throughout the design and implementation process.

This phase focused on co-design, iterative prototyping and framework validation in authentic low-resource conditions.

2. Secondary context—SLEP Valparaíso network (External validation):

To examine the transferability and acceptance of the proposed framework in broader educational settings, a complementary evaluation was conducted with 35 students (ages 11–16) and 7 teachers from public schools belonging to the Local Public Education Service (SLEP) of Valparaíso, Chile. This phase assessed user experience, visual appeal, emotional engagement, and perceived acceptance of the robot and its associated learning

activities. The data collected in this stage informed the refinement of the inclusivity and user-centered process dimensions of the framework.

All participants provided informed consent, and procedures were approved under institutional ethical research protocols.

3.4. Technical Implementation and Hardware Architecture

To operationalize and empirically examine the Robo-ICARE framework, a reference robotic instantiation was developed to embody the framework's Embodiment, Interactivity, and Intelligence dimensions under realistic classroom constraints. Rather than serving as a technological contribution, this instantiation was designed as an analytical vehicle to explore how framework-driven design principles can be enacted in under-resourced educational environments.

From a design perspective, the hardware architecture prioritized affordability, durability, offline operation, and emotional expressiveness, reflecting the contextual and pedagogical constraints identified during the contextual inquiry phase. The system integrates basic sensing, actuation, and expressive capabilities sufficient to support multimodal interaction, rule-based autonomy, and emotionally legible behavior, without reliance on advanced computation or continuous internet connectivity.

Consistent with Low-Cost Educational Robotics (LCER) principles, the architecture is modular and based on open-source components, enabling maintainability, adaptability, and classroom-level scalability. Importantly, technical design choices were guided by child-robot interaction (cHRI) considerations rather than by performance optimization, ensuring that expressive interaction and pedagogical alignment remained central.

Detailed hardware specifications, component lists, and construction procedures are provided in Appendix A to support transparency and replicability, while the main text focuses on the analytical role of the technical instantiation in validating the Robo-ICARE framework.

3.5. Evaluation Methods

A mixed-methods evaluation strategy was employed to support the formative validation of the Robo-ICARE framework, combining quantitative usability measures with qualitative observational and reflective data (Table 4). Rather than assessing system performance or learning outcomes in isolation, the selected instruments were used as analytical lenses to examine how the framework's design dimensions manifested during authentic classroom interaction.

Table 4. Framework-oriented evaluation methods.

Instrument	Purpose	Related Dimensions
System Usability Scale (SUS) [42]	Examine perceived usability as an indicator of alignment between embodiment, interaction design, and classroom constraints.	Embodiment, Interactivity.
User Experience Questionnaire (UEQ) [43]	Assess attractiveness, stimulation, and novelty as experiential indicators of emotionally expressive interaction.	Embodiment, Intelligence.
Classroom observations and Video logs	Document engagement, collaboration, and interaction patterns during framework-guided activities.	Inclusivity, Interactivity.
Teacher Interviews and Reflection logs	Examine pedagogical relevance, curricular integration, and perceived feasibility of framework-guided robotics activities.	Pedagogical alignment, user-centered process.
Student Reflections & Surveys	Capture affective responses, motivation, and perceived emotional connection during interaction.	Inclusivity, Embodiment.

Quantitative instruments provided descriptive indicators of perceived usability, attractiveness, and emotional engagement, while qualitative methods captured interaction patterns, pedagogical integration, and affective responses. This triangulation enabled a holistic examination of framework feasibility, experiential coherence, and contextual relevance, consistent with the design-based research approach adopted in this study.

Together, these methods were used to evaluate the Robo-ICARE framework at an experiential and design level, rather than to benchmark a specific robotic system.

4. Empirical Validation of the Robo-ICARE Framework

The Robo-ICARE framework for inclusive educational robotics was empirically validated through its operationalization in authentic educational contexts. A low-cost and emotionally expressive educational robot (COODI) was used as a reference instantiation to examine how the framework's design dimensions manifest in practice, rather than as the primary object of analysis. The validation focused on assessing the framework's feasibility, coherence, and experiential relevance in under-resourced and multigrade classroom settings.

4.1. Validation Objectives and Research Focus

The validation process was guided by the study's research objectives and questions, which were reformulated as framework-level validation criteria. These criteria were used to examine how effectively Robo-ICARE supports the design, implementation, and educational use of inclusive and emotionally expressive educational robots.

Accordingly, the validation focused on three main educational and experiential dimensions:

1. To assess the usability and emotional engagement as indicators of how the framework supports intuitive and affectively meaningful interaction.
2. To examine learning-related engagement and collaboration during STEM and introductory AI-related activities, as manifestations of pedagogical alignment and inclusivity.
3. To explore teacher's perceptions of pedagogical relevance and curricular integration, as indicators of contextual feasibility and sustainability.

These objectives were addressed through the following research questions (RQs):

- RQ1: How do students perceive the usability expressiveness of COODI during STEM activities?
- RQ2: How does framework-guided interaction support student engagement and collaboration in a rural multigrade classroom context?
- RQ3: How do teachers evaluate the pedagogical relevance and curricular integration of a Robo-ICARE-guided educational robotics implementation?

Overall, applying the framework was expected to support the design of emotionally engaging, pedagogically aligned, and inclusive educational robotics experiences, reflected in positive usability perceptions, engagement patterns, and teacher acceptance.

4.2. Contextual Inquiry

The first stage of the Robo-ICARE validation focused on contextual inquiry, aimed at understanding the pedagogical, infrastructural, and affective conditions shaping educational robotics adoption in rural and multigrade schools in Chile. This phase informed the inclusivity, pedagogical alignment, embodiment, and user-centered process dimensions of the framework.

Although Chilean public education has made progress in digital inclusion, contextual analysis revealed persistent structural and pedagogical constraints affecting robotics integration. Rather than being reported as implementation issues, these constraints were

analytically interpreted as design conditions that the framework needed to address. Key contextual factors included the following:

- Limited technological infrastructure and outdated equipment.
- Unreliable or absent internet connectivity.
- Limited teacher training in STEM and robotics methodologies.
- Restricted access to professional development.
- Curriculum overload and perception of robotics as extracurricular.
- Low interdisciplinary integration of STEM subjects.
- Limited use of available digital resources.

These conditions highlight systemic barriers commonly faced in under-resourced educational environments, while also underscoring the potential role of robotics as a mediating tool for inclusive, interdisciplinary, and affective learning when appropriately designed.

To ground the framework in real educational practice, contextual inquiry was conducted in a rural multigrade public school in Petorca, Chile. Data collection included classroom observations, informal interviews, and infrastructure mapping, enabling identification of environmental constraints and pedagogical opportunities relevant to inclusive robotics design. The analysis revealed a need for emotionally engaging, age-adaptable, and low-cost robotics solutions capable of functioning without continuous internet access.

Semi-structured interviews with seven teachers from public schools further informed the framework's pedagogical assumptions. Analysis revealed heterogeneous familiarity with STEM education and limited prior experience with robotics-based learning. Despite this, teachers expressed strong interest in educational robotics as a means to foster logical reasoning, creativity, teamwork, and problem-solving. These findings reinforce the importance of teacher mediation, curricular alignment, and professional support as core considerations within the Robot-ICARE framework.

4.3. Co-Design and Ideation

The co-design and ideation stage corresponded to the second validation phase of Robo-ICARE and aimed to translate contextual insights into framework-informed design principles. This stage primarily operationalized the User-Centered Process dimension by actively involving teachers and students as co-design participants rather than as end users.

Participatory sessions were conducted with students (ages 9–14) and teachers in a rural multigrade school. Rather than focusing on specific artifacts or activities, these sessions elicited user expectations, emotional preferences, and pedagogical constraints relevant to inclusive educational robotics. The outcomes informed framework-level decisions related to embodiment, interactivity, and emotional expressiveness, ensuring that subsequent instantiations were contextually meaningful and pedagogically feasible.

4.3.1. Derivation of User Requirements

Insights from the participatory sessions were synthesized into a set of functional and non-functional design constraints, mapped to established principles of educational robotics and child–robot interaction (CHRI), as summarized in Table 5.

Importantly, these requirements were not treated as implementation specifications, but as analytical constraints guiding how the Robo-ICARE framework dimensions were instantiated in practice. They informed decisions related to multimodal interaction, emotional expressiveness, robustness in low-resource environments, and curricular alignment, thereby supporting systematic examination of the framework's applicability under real classroom conditions.

Table 5. Framework—informed design constraints derived from participatory co-design.

Category	Design Constraint (Framework-Level)	Underlying Design Principle	Relevance to Robo-ICARE Dimensions
Child–Robot Interactivity	Interaction must support immediate, perceivable feedback loops that sustain engagement and turn-taking in collaborative learning activities.	Tangible interaction; affective feedback.	Interactivity; embodiment.
Emotional Expressiveness	Emotional states should be communicated through multimodal non-verbal cues (movement, light, sound) to support emotional engagement and relational perception.	Emotional Engagement; relational affordances.	Embodiment; interactivity.
Programming Modalities	Programming interaction must allow age-appropriate scaffolded engagement through visual or block-based representations.	Developmental appropriateness; scaffolding.	Pedagogical alignment; inclusivity.
Contextual Interaction	The system should enable embodied interaction with the environment to support situated and experiential learning.	Situated Learning, multimodal perception	Intelligence; interactivity.
Robustness and Usability	Design must tolerate variability in classroom conditions and minimize cognitive and technical overhead during use.	Ease of use; context awareness	Inclusivity; user-centered process.
Curricular Alignment	Robotics activities should align with curricular STEM and introductory AI learning objectives rather than function as isolated enrichment tasks.	Pedagogical Relevance	Pedagogical alignment.
Connectivity constraints.	Interaction should not rely on continuous internet connectivity and must function in offline or low-connectivity environments.	Flexibility; accessibility	Inclusivity; intelligence
Modularity and Scalability	Design should support incremental complexity to accommodate heterogeneous learner progression.	Progressive complexity	Intelligence; pedagogical alignment
Cost and accessibility	Materials and components must remain affordable and locally accessible to reduce structural barriers to adoption.	Equity, Access	inclusivity
Physical Portability	The robot’s physical form should support easy handling and movement within classroom settings	practicality	Embodiment, inclusivity
Appearance and social perception	The robot’s appearance should foster approachability and emotional connection without reliance on anthropomorphic realism.	Engagement; anthropomorphisms	Embodiment; emotional expressiveness.

4.3.2. Integration with Framework Dimensions

The outcomes of the co-design phase validated the relevance of the User-Centered Process as a core framework dimension. The direct involvement of students and teachers influenced design choices associated with Embodiment (physical form and expressivity), Interactivity (multimodal feedback), and Intelligence (rule-based autonomy). Grounding this decision in local educational and emotional contexts ensured that the case study implementation was not only technically feasible, but also socially and pedagogically coherent.

4.4. Prototyping and Technical Development

The prototyping stage focused on the operationalization of the Robo-ICARE framework through a functional reference instantiation, rather than on the development of a technological artifact per se. A low-cost educational robot was employed as an empirical vehicle to examine how the framework's design dimensions—particularly embodiment, interactivity, and intelligence can be instantiated under the constraints of under-resourced and offline classroom environments.

Following a User-Centered Design (UCD) approach, iterative prototyping cycles were conducted to explore the coherence between technical feasibility, emotional expressiveness, and pedagogical intent. From a research perspective, the purpose of this stage was not to optimize system performance or introduce novel hardware solutions, but to assess whether the design principles articulated by Robo-ICARE could be meaningfully enacted and experienced in practice. For this reason, detailed hardware specifications and construction procedures are reported in the Appendix, while the main text focuses on analytical implications for framework validation.

4.4.1. Affective and Pedagogical Integration

Within the framework operationalization, affective expressiveness was implemented through coordinated non-verbal cues, including movement, light, and sound. These expressive mechanisms served to instantiate the Embodiment and Interactivity dimensions of Robo-ICARE by enabling emotionally legible interaction without reliance on anthropomorphic features or advanced artificial intelligence. Rather than being treated as interface embellishments, expressive behaviors functioned as mediating elements supporting engagement, attention, and relational perception during learning activities.

At the pedagogical level, learning activities were structured using the Narrative-Driven Constructionist Cycle (NDCC) (Figure 2) as an instructional scaffold aligned with constructionist learning principles. NDCC was employed not as an independent pedagogical contribution, but as a means to ensure pedagogical alignment between emotionally expressive interaction, hands-on construction, and reflective learning processes. Through this integration, the framework enabled examination of how affective interaction and pedagogical structure jointly support meaningful engagement in STEM and introductory AI-related activities.



Figure 2. NDCC pedagogical model proposed.

4.4.2. Hardware Architecture

The hardware architecture of COODI was designed as a low-cost, modular, and robust platform to support offline operation and multimodal interaction in under-resourced educational contexts. Rather than emphasizing specific components, the design focused on enabling basic sensing, actuation, and expressive outputs required to operationalize the

Embodiment, Interactivity, and Intelligence dimensions of the Robo-ICARE framework. In particular, the platform supports rule-based autonomy and affective communication through coordinated movement, light, and sound, allowing students to explore fundamental concepts related to perception, decision-making, and non-verbal expression. Detailed hardware specifications and implementation procedures are provided in Appendix A.

4.4.3. Design Rationale and Framework-Oriented Comparative Analysis

The design of the reference instantiation used in this study is not intended to introduce a novel robotic platform, but to empirically examine how the Robo-ICARE framework can be operationalized in under-resourced educational contexts. Accordingly, design decisions were guided primarily by the framework’s dimensions—rather than by technological innovation or performance optimization—allowing the analysis to focus on design coherence, pedagogical alignment, and affective interaction.

From a framework-oriented perspective, the comparative analysis situates this instantiation within the broader landscape of educational robotics to clarify which design priorities emerge when inclusivity, emotional expressiveness, and contextual feasibility are treated as primary constraints. In contrast to commercially available platforms such as LEGO EV3 or Makeblock mBot, which emphasize programmability, modularity, and advanced sensing capabilities, the framework-guided instantiation prioritizes emotionally legible interaction, offline operation, and adaptability to heterogeneous classroom conditions. These priorities reflect the pedagogical and infrastructural realities of multigrade and low-resource educational settings.

Table 6 summarizes this comparison across analytically relevant dimensions, including emotional expressiveness, programming modality, connectivity requirements, modularity, and pedagogical focus. Importantly, this comparison does not aim to rank platforms according to technical sophistication. Instead, it serves as an analytical lens to illustrate how different underlying design assumptions lead to divergent educational affordances.

Table 6. Comparative Analysis of COODI and other educational robots.

Feature/Robot	COODI	LEGO EV3	Makeblock mBot	KIBO
Design Origin	Co-designed with students & teachers (UCD)	Developed by LEGO Education	Developed by Makeblock	Developed by DevTech (Tufts)
Target Context	Rural multigrade schools	Formal STEM classrooms	Formal/informal STEM contexts	Early education (PreK–2nd grade)
Emotional Expressiveness	Yes (LEDs, head movement, sound)	Limited (screen interface only)	Limited (lights/sound)	No
Programming Interface	Block-based (Blockly, local/offline support)	Graphical (Scratch/ EV3 software)	mBlock (Scratch-based)	No-code tangible blocks
Internet Dependence	No (can operate offline)	Yes (for full functionality)	Yes	No
Modularity & Scalability	High (expandable hardware)	Medium	Medium	Low
Cost	Low (open-source + 3D printed)	High	Medium	Medium to High
Construction Approach	DIY with 3D printing and basic components	Pre-built modules	Metal & electronic components	Wooden blocks
Pedagogical Focus	STEM + AI + Emotional Learning	STEM/Engineering	STEM/Robotics	Creative play & sequencing
Development Framework	UCD + Affective + Constructionism	Engineering design process	STEM design challenge	Constructionism (Papert)

Overall, this comparative analysis reinforces that the distinctiveness of the reference instantiation lies in its role as an applied operationalization of the Robo-ICARE framework. More broadly, it demonstrates how a framework-driven approach can yield educational robotics designs that are emotionally expressive, pedagogically grounded, and feasible within the constraints of under-resourced classroom environments.

4.4.4. Reflection and Validation Within the Framework

The prototyping and technical development stage provided an opportunity to reflect on and preliminarily validate the Robo-ICARE framework through its operationalization in an authentic educational context. Rather than evaluating a specific robotic artifact, this stage examined whether the framework's design dimensions could be coherently instantiated and experienced within the constraints of low-resource, offline classroom environments.

At the framework level, the coordinated integration of Embodiment (physical presence and emotional expressiveness), Interactivity (multimodal feedback), and Intelligence (rule-based autonomy) supported intuitive interaction patterns and sustained engagement. Observations and formative feedback collected from students and teachers during iterative prototyping cycles indicated improvements in perceived usability, contextual relevance, and learner ownership of the activities. These outcomes reinforce the importance of the User-Centered Process dimension as a mechanism for aligning design intent with classroom realities.

From a validation perspective, this stage did not seek to assess technical performance or learning gains in isolation. Instead, it functioned as an analytical checkpoint to examine whether the design principles articulated by Robo-ICARE could be meaningfully applied and interpreted in practice. The findings suggest that the framework offers a viable and internally coherent structure for guiding the design of inclusive and emotionally expressive educational robotics, even in contexts characterized by limited resources and heterogeneous learner needs.

Overall, this reflective analysis supports the role of Robo-ICARE as a design-guiding and empirically grounded framework that bridges technical feasibility, affective interaction, and pedagogical intent, while also identifying directions for future refinement and extension.

4.5. Educational Design and Implementation

The educational design and implementation stage focused on applying the Robo-ICARE framework within authentic classroom environments, with the aim of examining its pedagogical alignment, inclusivity, and user-centered process dimensions in practice. COODI was employed as a case study to explore how the framework's design principles could be enacted through structured learning activities in under-resourced educational contexts.

Building on the affective and pedagogical integration described in Section 4.4.1, the learning activities were designed to promote active participation, collaboration, and reflection, while remaining aligned with curricular objectives and contextual constraints. Within this structure, robotics functioned as a mediating artifact that supported engagement with STEM and foundational AI-related concepts through hands-on exploration and emotionally meaningful interaction.

Overall, this stage demonstrates how the Robo-ICARE framework can guide the implementation of inclusive educational robotics initiatives in real classroom settings, ensuring coherence between design intentions, pedagogical goals, and learner experience without reliance on advanced or adaptive AI mechanisms.

4.5.1. Workshops Design

The workshops were designed as structured learning scenarios to operationalize and examine the ICARE framework within real classroom settings. Rather than functioning as standalone instructional units, the workshops served as pedagogical instruments to enact the framework's pedagogical alignment, inclusivity, and user-centered process dimensions through hands-on and collaborative activities.

A total of six workshops were implemented, each addressing progressive levels of interaction with the robot, including assembly, basic programming, emotional expressiveness, sensor-based behavior, and personalization. The sequence of workshops was intentionally designed to support gradual engagement with STEM and foundational AI-related concepts, while accommodating heterogeneous skills levels typical of multigrade classrooms. Key learning objectives and their alignment with workshop themes are summarized in Table 7.

Table 7. Description of workshops implemented with COODI.

Workshop Title	Learning Outcomes (LO)	Duration (min)
Assembling COODI	LO1: Interpret diagrams and instructions. LO2: Assemble 3D parts correctly. LO3: Develop spatial reasoning and attention to detail. LO4: Foster teamwork and coordination.	90
Preparing COODI's Energy	LO1: Understand electric circuits and motor operation. LO2: Apply block-based programming to control movement. LO3: Debug and optimize performance. LO4: Promote team collaboration and role assignment.	90
Shaking His Head	LO1: Understand servo motors and angular movement. LO2: Introduce cycles and variables in programming. LO3: Troubleshoot servo errors. LO4: Practice collaborative assembly and testing.	90
Programming Emotional Expressions	LO1: Understand RGB color mixing and NeoPixel control. LO2: Associate colors with emotions. LO3: Program expressive sequences using LEDs and movement. LO4: Design creative emotional outputs collaboratively.	90
Putting Eyes on the Robot	LO1: Understand ultrasonic sensors and their analogy with echolocation. LO2: Program rule-based behavior (if-then). LO3: Analyze sensor input and actuator output relationships. LO4: Apply logic in problem-solving scenarios collaboratively.	90
Personalizing the Robot	LO1: Use 3D pen tools to design accessories. LO2: Enhance fine motor skills through modeling. LO3: Foster creativity and personal expression. LO4: Reflect on customization as a form of identity and engagement with technology.	90

The workshop design emphasized collaborative work, creative exploration, and reflective discussion, enabling students to actively construct knowledge while engaging emotionally with the robot. Teachers acted as facilitators rather than instructors, adapting activities to contextual constraints such as limited infrastructure and time availability. This design approach ensured that the workshops remained flexible inclusive, and responsive to the educational realities of under-resourced school environments.

4.5.2. Learning Approach and Pedagogical Strategy

The learning approach adopted in this study was grounded in constructionist and child-centered pedagogical principles, emphasizing active participation, collaboration, and reflection. Rather than delivering predefined content, learning activities were designed

to position students as active creators, allowing them to explore STEM and foundational AI-related concepts through hands-on interaction with the robot.

Within this approach, the Robo-ICARE framework guided pedagogical decision-making by ensuring coherence between technical design, emotional engagement, and educational objectives. Activities promoted collaborative problem-solving, iterative experimentation, and expressive interaction, enabling students to engage with both cognitive and affective dimensions of learning. This strategy was particularly relevant for multigrade classrooms, where differentiated pacing and peer-supported learning are essential.

Overall, the learning approach functioned as a mediating layer between the framework and classroom practice, supporting inclusive participation and meaningful engagement without reliance on advanced or adaptive AI mechanisms. This alignment reinforces the role of Robo-ICARE as a pedagogically informed framework capable of guiding educational robotics initiatives in under-resourced contexts.

4.5.3. Observations During Implementation

Observational data indicated a steady increase in student engagement, confidence, and collaboration.

Students who had no prior exposure to robotics showed rapid progress in basic programming and mechanical understanding, alongside strong emotional attachment to COODI.

They frequently referred to the robot as a peer or classmate, demonstrating the role of emotional design in sustaining motivation. Teachers reported that the workshops activated cross-curricular learning, linking robotics to science, art, and language through storytelling and creative design.

This alignment with the national STEM + AI curriculum confirmed the effectiveness of the framework's Pedagogical Alignment dimension. Challenges observed included interpreting wiring diagrams and handling delicate components; however, these were mitigated through peer assistance and teacher facilitation, validating the framework's emphasis on User-Centered Process and adaptability.

4.5.4. Educational Impact and Reflection

By integrating affective expression with STEM learning, the workshops validated the framework's capacity to produce emotionally engaging, contextually adaptable, and inclusive educational experiences.

Students demonstrated growth in collaboration, perseverance, and creative problem-solving, while teachers highlighted the potential of COODI to reduce digital inequities and support 21st century skill development in rural contexts.

The educational design and implementation stage thus confirmed that applying the cHRI framework leads to robotics-based learning that is not only technically functional but also socially and pedagogically transformative, aligning emotional interaction with cognitive and collaborative development.

4.6. Evaluation and Refinement

The evaluation and refinement stage represented the fifth phase. This phase aimed to assess and improve the framework's six core dimensions embodiment, interactivity, intelligence, pedagogical alignment, inclusivity, and user-centered process through systematic evaluation of the design, implementation, and learning outcomes obtained with the COODI robot.

A mixed-methods approach was applied to ensure comprehensive validation, combining quantitative usability metrics with qualitative observations and teacher reflections. This triangulation of data allowed for a holistic understanding of how effectively the framework

supported usability, engagement, emotional connection, and pedagogical integration in a real educational environment.

4.6.1. Evaluation Design

The evaluation was organized around three analytical dimensions derived from the study's objectives: (1) usability and emotional engagement; (2) learning outcomes and collaboration, and (3) Pedagogical relevance and inclusivity.

Quantitative data were collected using the System Usability Scale (SUS) and User eXperience Questionnaire (UEQ) to measure perceived usability and emotional appeal, while qualitative data were obtained through classroom observations, teacher interviews, and reflection logs. Together, these instruments provided a detailed picture of both the technical and emotional performance of the COODI implementation.

4.6.2. Quantitative Evaluation

- **System Usability Scale (SUS):** Administered to 14 students and 2 teachers after the implementation of all workshops, the SUS yielded an average score of 65 students (acceptable) and 79 for teachers (good). Figure 3 shows the SUS scores obtained by each student. Positive statement responses were normalized by subtracting 1 from the score, and negative ones by subtracting the score from 5. The resulting values were summed and multiplied by 2.5 to calculate each student's SUS score. The average score across students was 65, indicating acceptable usability with room for improvement. In the open-ended question "What was the most difficult part?", most students cited either head assembly or the use of the breadboard.

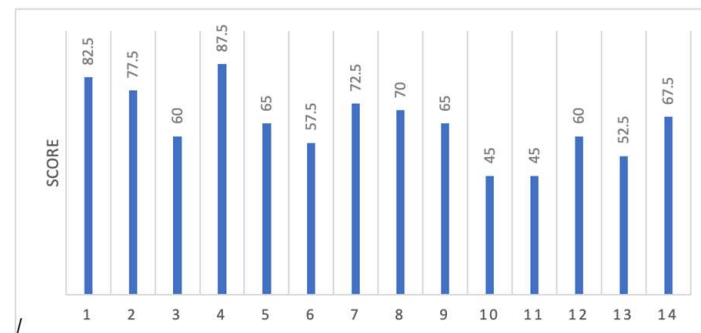


Figure 3. Results obtained for each student (SUS scores).

- **User Experience Questionnaire (UQE):** Completed by two teachers, reflecting positive user perceptions across all six dimensions, especially attractiveness (3.0), stimulation (2.8) and novelty (2.7), indicating that COODI's emotional expressiveness enhanced learning motivation. The lowest score, perspicuity (1.9), suggested the need for clearer assembly and programming instructions, which informed subsequent design improvements. Figure 4 presents the teacher's evaluations of COODI across six UEQ dimensions: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. All dimensions scored positively, particularly in Stimulation and Novelty, indicating that the robot was perceived as engaged and innovative. The color bands indicate the interpretation scale: Green: positive evaluation (above 0.8), Yellow: neutral range (between -0.8 and 0.8) and Red: negative evaluation (below -0.8). The results suggest a favorable overall user experience, with mirror areas for improvement in clarity (Perspicuity). The short vertical lines shown for *Perspicuity* and *Novelty* represent the standard error of the mean for these dimensions.

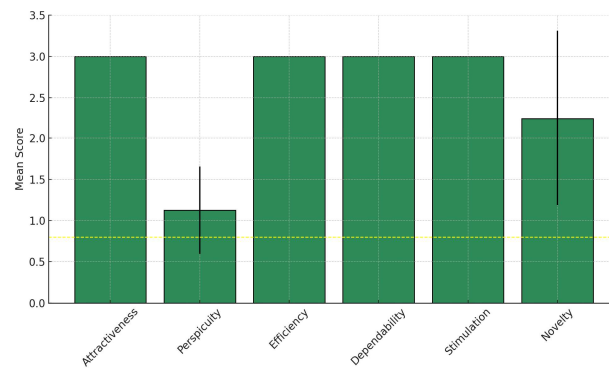


Figure 4. Results obtained from UEQ (teacher responses).

The bar chart shows the average scores given by teachers for six UEQ dimensions: Attractiveness, Perspicuity, Efficiency, Dependability, Stimulation, and Novelty. Most dimensions received the maximum score (3.0), while Perspicuity scored slightly lower, indicating a potential area for improvement in ease of use or learnability. Error bars represent the standard deviation. The yellow dashed line marks the neutral evaluation threshold (0.8).

The results suggest that COODI succeeded in motivating students through hands-on interaction, especially in assembly and expressive behavior. Nonetheless, several usability improvements were identified. The head assembly was found to be one of the main difficulties due to unclear instructions and visual ambiguity. Based on user observations, changes were made to improve clarity and robustness: a color-coded 3D part was added to distinguish facial elements, and a custom shield was developed to simplify the connection of mechatronic components using Dupont cables.

To complement the usability (SUS) and user-experience (UEQ) analyses, a third evaluation was conducted with 35 students aged 11 to 16, enrolled in 6th grade, 7th grade, and 3rd year of secondary education from public schools belonging to the Local Public Education Service (SLEP) of Valparaíso, Chile. This phase aimed to assess students' perceptions, emotional engagement, and acceptance of COODI while learning basic programming through block-based coding activities.

A child-friendly questionnaire, titled “how was your experience with COODI?”, was administered at the end of the workshop. It included nine items combining smiley-scale ratings, multiple-choice options, and open-ended question to capture both quantitative and qualitative aspects of user experience. The instrument focused on four key dimensions such as (1) visual appeal; (2) perception of emotional expressiveness; (3) appreciation of lights and sounds, and (4) overall acceptance and willingness to use the robot again. Table 8 shows a summary of questionnaire results on student experience ($n = 35$).

Table 8. Summary of questionnaire results of student experience ($N = 35$).

Dimension	Item (Question)	Main Indicators	Positive Responses (%)
Visual appeal	Q1—Do you like how COODI looks?	“Loved it” (65.7%) + “Liked it” (28.6%)	94.3%
Perceived emotional expressiveness	Q3—Does COODI seem to have emotions or feelings?	“Yes, through colors or sounds” (60.0%) + “Yes, when it moves its head” (5.7%)	65.7%
Appreciation of lights and sounds	Q4—Did you like COODI’s lights and sounds?	“Yes, a lot” (80.0%) + “A little” (17.1%)	97.1%
Overall acceptance	Q9—Would you like to have COODI at home or at school?	“I’d love to have one” (91.4%) + “Only at school” (2.9%)	94.3%

Figure 5 shows a radar chart visualizing the overall perception and acceptance profile of COODI, where it clearly shows the strong peaks for visual appeal, lights and sounds, and overall acceptance, with slightly lower but still positive scores for emotional expressiveness.

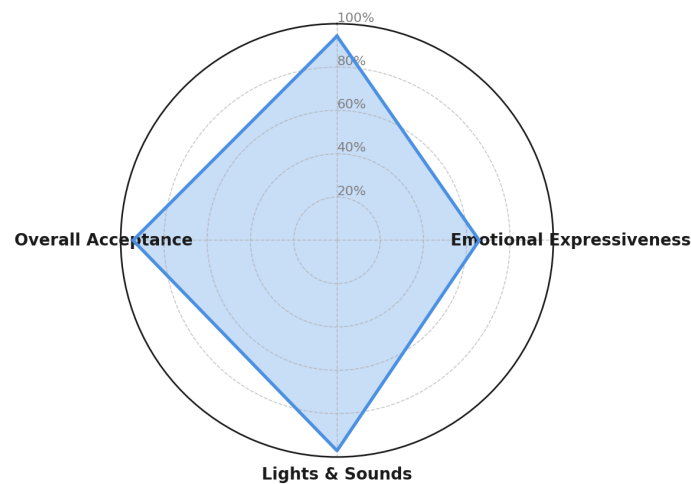


Figure 5. Overall perception and acceptance COODI ($n = 35$).

The results demonstrate high acceptance, motivation, and satisfaction with COODI among students from public SLEP schools in Valparaíso. The robot's multimodal expressiveness integrating movement, light, and sound was central to fostering engagement and emotional connection during block-based programming tasks. These outcomes reinforce COODI's potential as a socially engaging and affective learning companion that support inclusive STEM and AI education across both primary and secondary school contexts. Open-ended responses revealed a strong affective connection with the robot. Students describe COODI as “fun”, “friendly”, “intelligent”, and “different”, often perceiving it as a companion rather than a machine. Common improvement suggestions included adding voice interaction, faster movement, and protective cover for cables to make it appear “more alive”. Teacher field notes supported these perceptions, reporting greater curiosity, collaboration, and participation, particularly among students with limited prior experience in robotics or programming.

Figure 6 shows a heatmap showing the percentage of positive responses by age group (11–12, 13–14, 15–16, 17+) and dimension. The visualization reveals that (1) younger students (11–12 years) show the highest engagement and emotional perception especially for light and sounds and visual appeal; and (2) older students maintain strong acceptance and visual appreciation, though slightly lower emotional expressiveness scores.

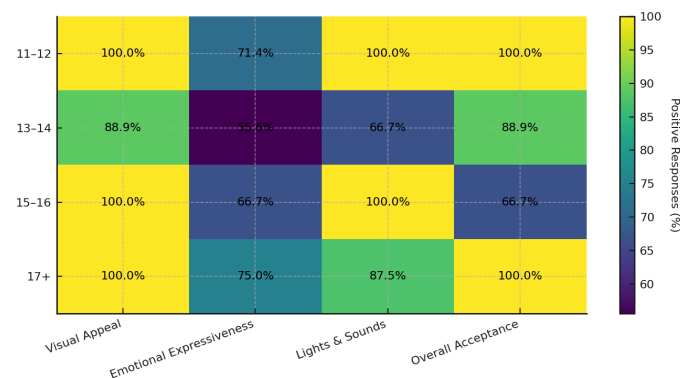


Figure 6. Positive perception of COODI by age group and dimension.

- Spearman Correlation Analysis

To explore potential relationships between students' perceived usability of the COODI robot and other observed and performance-based variables, a Spearman correlation analysis was conducted. The variables included the following: SUS Score, Observed Participation, Sequence Task Score (cognitive performance during the programming activity), and Collaboration level.

Given the small sample size ($n = 14$) and the ordinal nature of the data, Spearman's rho was selected as a suitable non-parametric test. The correlation matrix is presented in Figure 7.

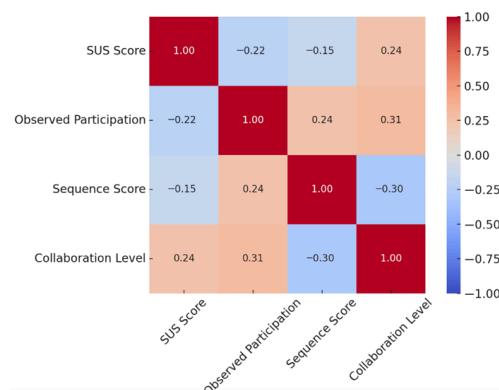


Figure 7. Spearman correlation matrix among key study variables.

- A weak positive correlation was found between SUS Score and Collaboration Level ($\rho = 0.24$), suggesting that students who collaborated more actively tended to perceive the robot as more usable.
- A similar weak correlation was observed between Observed Participation and Sequence Score ($\rho = 0.24$), indicating that students who participated more actively generally performed better in computational thinking tasks.
- A moderate negative correlation was observed between Collaboration Level and Sequence Score ($\rho = -0.30$). This may reflect the distribution of roles within pairs (e.g., one student focusing on discussion/collaboration while the other performed the task).

None of the correlations were statistically significant ($p > 0.05$), which is consistent with the exploratory nature of the study and its small sample. However, these findings provide useful insights and support future hypothesis generation in educational robotics studies.

4.6.3. Qualitative Evaluation

The qualitative evaluation complemented quantitative results by analyzing observations, teacher interviews, and reflection logs collected during the COODI workshops.

Findings revealed high student engagement and collaboration, with learners showing curiosity, empathy, and teamwork even without prior experience in robotics.

Students frequently referred to COODI as a *friend* or *team member*, demonstrating affective connection consistent with the framework's Embodiment and Interactivity dimensions.

Teachers reported that COODI supported Pedagogical Alignment by integrating STEM concepts with creativity and emotional learning. The activities fostered communication, problem-solving, and interdisciplinary thinking, validating the use of robotics as a bridge between science, art, and language. Participation was inclusive across genders and ability levels, with the robot's multimodal expressiveness enabling all students to contribute meaningfully—evidence of the framework's Inclusivity principle. Teachers emphasized

that iterative facilitation and student feedback improved usability and motivation, reinforcing the User-Centered Process dimension.

Overall, the qualitative evidence confirmed that applying the *cHRI framework* led to emotionally engaging, inclusive, and pedagogically coherent learning experiences in real classroom settings.

4.7. Dissemination and Scalability

This stage represented the final phase of the framework. Its objective was to ensure that the framework, tools, and methodologies developed through the COODI case could be replicated, adapted, and sustained across diverse educational environments.

To promote scalability, the framework was implemented following a hub-and-satellite model.

The pilot school (*Escuela Juan Pablo II* in Petorca) served as the core hub for testing and refinement, while the SLEP Valparaíso Network functioned as an expansion node, involving 35 students and 7 teachers in the external validation phase.

This dual approach allowed testing of the framework's adaptability to different infrastructure levels, classroom sizes, and pedagogical practices.

Dissemination efforts focused on three key strategies:

1. Open-access materials—including 3-D printable designs, assembly guides, and workshop templates, published under open licenses for educational use;
2. Teacher professional development—capacity-building workshops emphasizing STEM + AI integration, emotional design, and inclusive pedagogy;
3. Community outreach—demonstrations and collaborative events promoting awareness of robotics as a tool for inclusion and creativity.

Preliminary replication results indicate that the framework can be effectively implemented with minimal resources and local materials, confirming its scalability and sustainability in low-resource educational contexts.

5. Discussion and Limitations

This study set out to examine the design and applicability of Robo-ICARE, a child-centered framework for inclusive educational robotics, through its operationalization in authentic classroom contexts. Rather than evaluating the performance of a specific robotic system, the research focused on understanding how a set of interrelated design dimensions—embodiment, interactivity, intelligence, pedagogical alignment, inclusivity, and user-centered process—can guide the creation of emotionally engaging and context-sensitive educational robotics experiences in under-resourced environments.

5.1. Framework-Level Interpretation of Findings

At the framework level, the findings indicate that Robo-ICARE provides a coherent analytical structure for integrating technical, pedagogical, and affective considerations in educational robotics design. The usability, engagement, and emotional acceptance results observed across implementations suggest that these dimensions do not operate independently but rather function as mutually reinforcing components of inclusive child-robot interaction. In particular, emotional expressiveness emerged as a mediating design mechanism that supported engagement and collaboration, rather than as a peripheral or aesthetic feature.

The acceptable usability scores reported in the System Usability Scale (SUS) should be interpreted considering the study's ecological context. In design-based research conducted in rural and multigrade classrooms, usability friction often reflects authentic infrastructural and pedagogical constraints rather than deficiencies in design. From a framework vali-

dation perspective, these findings underscore the importance of treating usability not as an isolated metric, but as an indicator of alignment between design intent and contextual realities [26,29].

5.2. Emotional Expressiveness as Pedagogical Mediator

One of the central contributions of Robo-ICARE lies in its explicit treatment of emotional expressiveness as a pedagogical mediator. The positive perceptions reported by students and teachers suggest that multimodal non-verbal cues—such as movement, light, and sound—facilitated emotional connection, sustained attention, and peer collaboration. These results align with prior work in child–robot interaction, which emphasizes the role of embodied and affective communication in fostering motivation and social engagement.

Importantly, the study demonstrates that emotionally expressive interaction does not require anthropomorphic design or advanced artificial intelligence. Instead, relatively simple expressive mechanism, when pedagogically aligned and contextually grounded, can meaningfully enhance the learning experience. This insight is particularly relevant for under-resourced educational settings, where technical simplicity and robustness are essential design constraints.

5.3. Inclusivity and Pedagogical Alignment in Under-Resourced Contexts

The findings further suggest that inclusivity in educational robotics extends beyond accessibility at the hardware level. Within the Robo-ICARE framework, inclusivity is conceptualized as an emergent property resulting from the interaction between pedagogical alignment, user-centered processes, and emotionally supportive interaction. Observations of collaborative behavior, peer support, and broad participation across age and ability levels indicate that the framework supported meaningful engagement in heterogeneous classroom contexts.

From a pedagogical standpoint, the alignment of robotics activities with foundational STEM and introductory AI-related concepts proved critical for integration within existing classroom practices. Rather than positioning robotics as an extracurricular or enrichment activity, Robo-ICARE emphasizes curricular coherence, enabling robotics to function as a mediating artifact that supports interdisciplinary learning and creative problem-solving.

5.4. Design- Based Research and Framework Validation

Methodologically, this study illustrates the value of design-based research (DBR) for validating educational robotics frameworks. DBR enabled iterative refinement of Robo-ICARE through empirical observation, participatory design, and formative evaluation, while maintaining ecological validity. The use of mixed methods supported triangulation of experiential indicators, allowing the framework’s feasibility and relevance to be assessed without relying on controlled experimental designs or standardized learning outcomes.

Crucially, the framework’s validation does not rest on the success of a single technological instantiation. Instead, COODI functioned as an empirical vehicle through which the framework’s dimensions could be examined in practice. This distinction reinforces the generalizability of Robo-ICARE as a design-guiding framework rather than as a system-specific solution.

5.5. Implications for Educational Robotics and cHRI Research

Beyond the specific case study, Robo-ICARE contributes to educational robotics and child–robot interaction research by offering a process-oriented and empirically grounded framework for inclusive design. The framework shifts the focus from technological novelty toward design coherence, emotional engagement, and contextual relevance. It also demonstrates that meaningful child–robot interaction can be achieved without depen-

dence on advanced adaptive AI, making inclusive educational robotics more attainable for low-resource educational systems.

Future research may build upon Robo-ICARE by exploring its application across diverse cultural and educational contexts., integrating more advanced adaptive behaviors where appropriate, and examining long-term learning trajectories. However, the present findings already suggest that inclusive, emotionally expressive educational robotics can be systematically designed and evaluated using framework-driven approaches grounded in real classroom practice.

6. Conclusions

This study presented and examined Robo-ICARE, a child-centered framework for designing inclusive educational robotics grounded in principles of child–robot interaction, emotional expressiveness, pedagogical alignment, and user-centered design. Through a design-based research approach, the framework was operationalized and empirically examined in authentic classroom contexts, using a low-cost educational robot as a reference instantiation rather than as the primary research contribution.

At the framework level, the findings indicate that Robo-ICARE provides a coherent and transferable structure for integrating technical, pedagogical, and affective dimensions in educational robotics design, particularly in under-resourced and multigrade educational settings. The empirical results related to usability, user experience, and emotional acceptance suggest that emotionally expressive interaction can function as a pedagogical mediator, supporting engagement, motivation, and collaborative learning without reliance on advanced artificial intelligence or anthropomorphic design.

The case study implementation demonstrated that inclusive educational robotics does not depend solely on technological sophistication, but on the alignment between embodiment, interactivity, pedagogical intent, and participatory design processes. Observations across classroom implementations showed that multimodal non-verbal expressiveness—such as movement, light, and sound-supported emotional connection and sustained participation, reinforcing constructionist learning principles that emphasize active, exploratory, and socially situated learning.

Importantly, the study also highlights that educational robots should not be understood as standalone instructional solutions. Meaningful learning outcomes depend on the intentional design of pedagogical activities that frame robot use. Within Robo-ICARE, the robot functions as a mediating artefact whose educational value emerges from its integration into well-structured learning scenarios that promote problem-solving, creativity, collaboration, and reflection.

Several limitations must be acknowledged. The exploratory nature of the study, the relatively small sample size, and the focus on rule-based autonomy constrain generalizability and preclude causal claims regarding learning outcomes. In addition, contextual constraints such as limited connectivity, variable teacher technical experience, and material durability issues reflect the realities of under-resourced educational environments and underscore the importance of user-centered and context-sensitive design.

Future research should extend this work through longitudinal and cross-cultural studies, incorporating more robust learning assessments, comparison conditions, and where contextually appropriate, adaptive and data-driven behaviors. Such efforts would allow further examination of the framework’s applicability, scalability, and long-term educational impact.

In conclusion, this study demonstrates that inclusive, emotionally expressive educational robotics can be systematically designed and examined through framework-driven approaches grounded in real classroom practice. Robo-ICARE contributes to ed-

educational robotics and child–robot interaction research by shifting the focus from isolated technological artifacts to design coherence, emotional engagement, and pedagogical relevance, offering a replicable foundation for inclusive robotics in under-resourced educational contexts.

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Appendix A. Technical and Procedural Details—Hardware Architecture of COODI

The COODI robot was designed as a low-cost, modular, and durable educational platform to support offline operation and hands-on use in under-resourced classroom environments. Its hardware architecture allows teachers and students to assemble, operate, and maintain the robot without specialized tools or infrastructure, supporting accessibility and scalability in educational contexts.

The platform integrates a set of core components that enable basic sensing, actuation, and expressive interaction. These include an open-source microcontroller (Arduino UNO or ESP32), two DC motors for mobility, and a servo motor (SG/MG90) to support expressive head movement. Environmental perception is achieved through ultrasonic distance sensing, inertial measurement (IMU), and ambient light detection (LDR). For affective output, the robot incorporates an RGB LED ring (NeoPixel) to convey emotional states through color and intensity, complemented by auditory feedback via a buzzer.

Structurally, COODI is built on a 3D-printed chassis composed of three detachable modules—head, base and electronics bay—facilitating assembly, maintenance, and iterative modification. Local Bluetooth or Wi-Fi connectivity enables offline programming and data transfer, while interaction and control are implemented using age-appropriate, block-based programming environments (e.g., Blockly, mBlock), eliminating dependency on continuous internet access.

Figure A1 illustrates the evolution of the COODI prototype, from an initial low-fidelity version constructed with basic materials for early testing, to a high-fidelity 3D-printed prototype incorporating the final hardware and interaction components.

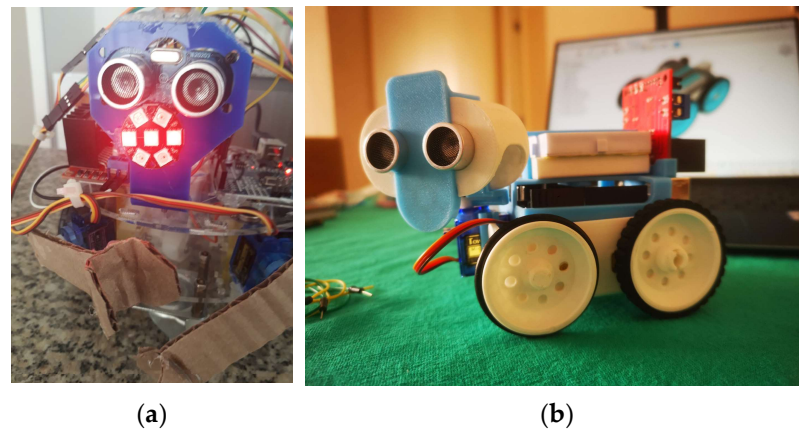


Figure A1. COODI Prototype: (a) low-fidelity prototype constructed with cardboard and basic materials for initial testing and exploration; (b) high-fidelity prototype based on 3D printing, incorporating the final hardware and interaction components.

Figure A2 shows the COODI parts lineup, that is, all the main components that make up the robot, likely arranged side by side or in sequence. It probably includes the head, base platform, electronic module (Arduino, sensors, motors), and other structural pieces, visually displaying the robot's modular architecture and how its sections fit together.

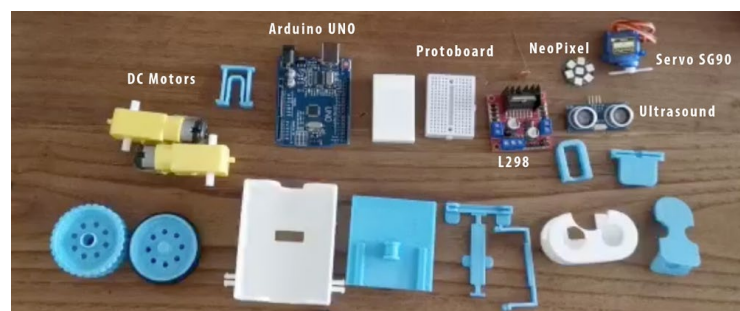
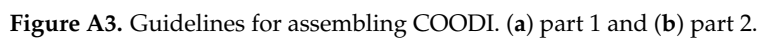


Figure A2. COODI parts lineup (See video).

Figure A3 presents the assembly guidelines developed to support the construction of the COODI robot by students and teachers in classroom settings. These guidelines were designed to minimize cognitive load and technical complexity, enabling independent or collaborative assembly without specialized tools. The visual instructions emphasize modularity and sequential organization, supporting accessibility and robustness in low-resource educational environments. Although these guidelines are not part of the main analytical contribution of the study, they illustrate how the User-Centered Process dimension of the Robo-ICARE framework was operationalized in practice.

Figure A4 illustrates examples of formative activities used to support the development of basic mathematical and computational thinking skills during the workshops. These activities were designed as complementary tasks to reinforce sequencing, logical reasoning, and problem decomposition through visual and interactive challenges. Rather than serving as standardized learning assessments, these formative exercises functioned as scaffolding mechanism to support engagement and to provide qualitative indicators of student's understanding during hands-on programming activities.



	8	12	3	6
9	13	6	7	2
1	0	2	3	11
4	17	1	4	7
23	2	14	5	=40

C		C		S
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Q	U	I	4	I
I	Q	Q	I	=CUIQUI

				
				
				
				
				7 

Figure A4. Formative evaluation integrating mathematical (a,b) and computational concepts (c).

Figure A5 shows representative examples of emotional expressions implemented in COODI using coordinated multimodal cues, including movement, light, and sound. These expressions were designed following emotion metaphor principles, allowing students to explore non-verbal emotional communication through programming. The figure illustrates how basic affective states were conveyed without anthropomorphic facial features, supporting emotional engagement while maintaining low-cost and technically simple design. These examples complement the discussion of affective expressiveness presented in the main text and provide additional insight into how the embodiment and interactivity dimensions of the CARE framework were instantiated.

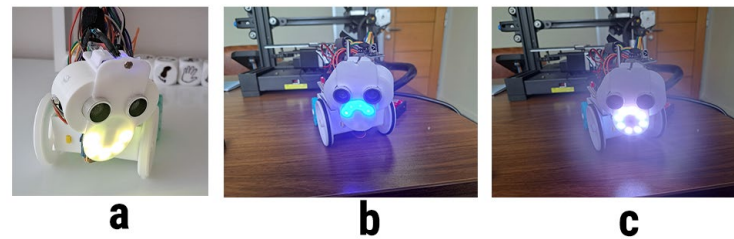


Figure A5. Emotional expressions: (a) happiness; (b) sadness; and (c) surprise.

Figure A6 presents an example of block-based programming used to implement emotional expressions in COODI through reusable functions. In this example, emotional behaviors are encapsulated as modular functions that coordinate light, movement, and sound outputs, allowing students to trigger complex expressive actions with simplified control structures. This programming approach supports fundamental computational thinking concepts such as abstraction, modularity, and code reuse, while maintaining accessibility for novice learners. The figure illustrates how emotional expressiveness was operationalized through rule-based logic, consistent with the introductory AI scope of the study and the intelligence dimension of the ICARE framework.

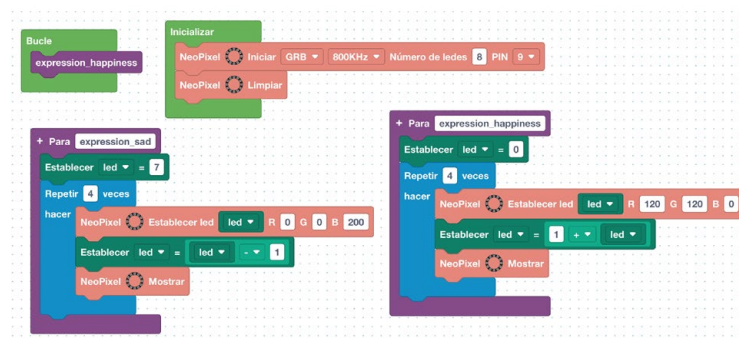


Figure A6. Example programming emotional expression using functions.

References

1. Anwar, S.; Bascou, N.A.; Menekse, M.; Kardgar, A. A Systematic Review of Studies on Educational Robotics. *J. Pre-Coll. Eng. Educ. Res. J-PEER* **2019**, *9*, 2. [\[CrossRef\]](#)
2. Musundire, A. Integrating Educational Robotics and Artificial Intelligence With African Educational Perspectives in Science, Technology, Engineering, and Mathematics: Challenges and Opportunities. In *Advances in Computational Intelligence and Robotics*; Sorayyaie Azar, A., Elyas, T., Muthmainnah, M., Curle, S., Eds.; IGI Global: Hershey, PA, USA, 2025; pp. 129–156. [\[CrossRef\]](#)
3. Ryalat, M.; Almtireen, N.; Al-refai, G.; Elmoaqet, H.; Rawashdeh, N. Research and Education in Robotics: A Comprehensive Review, Trends, Challenges, and Future Directions. *J. Sens. Actuator Netw.* **2025**, *14*, 76. [\[CrossRef\]](#)
4. Alam, A.; Mohanty, A. Integrated constructive robotics in education (ICRE) model: A paradigmatic framework for transformative learning in educational ecosystem. *Cogent Educ.* **2024**, *11*, 2324487. [\[CrossRef\]](#)
5. Piaget, J. Part I: Cognitive development in children: Piaget development and learning. *J. Res. Sci. Teach.* **1964**, *2*, 176–186. [\[CrossRef\]](#)
6. Papert, S. *Mindstorms: Children, Computers and Powerful Ideas*; Harvester Press: London, UK, 1982.

7. Papert, S. Microworlds: Transforming education. In *Artificial Intelligence and Education; Learning Environments and Tutoring Systems*; Ablex Publishing Corp.: New York, NY, USA, 1987; Volume 1.
8. Ching, Y.-H.; Hsu, Y.-C. Educational Robotics for Developing Computational Thinking in Young Learners: A Systematic Review. *TechTrends* **2024**, *68*, 423–434. [[CrossRef](#)]
9. Bashkireva, T.; Bashkireva, A.; Morozov, A.; Fedorchuk, Y.; Bakhtina, A. The value of digital technologies in inclusion. *SHS Web Conf.* **2022**, *141*, 03015. [[CrossRef](#)]
10. Castro, A.; Medina, J.; Aguilera, C.A.; Ramirez, M.; Aguilera, C. Robotics Education in STEM Units: Breaking Down Barriers in Rural Multigrade Schools. *Sensors* **2022**, *23*, 387. [[CrossRef](#)]
11. Funk, M.G.; Cascalho, J.M.; Santos, A.I.; Mendes, A.B. Educational Robotics and Tangible Devices for Promoting Computational Thinking. *Front. Robot. AI* **2021**, *8*, 713416. [[CrossRef](#)]
12. Belpaeme, T.; Kennedy, J.; Ramachandran, A.; Scassellati, B.; Tanaka, F. Social robots for education: A review. *Sci. Robot.* **2018**, *3*, eaat5954. [[CrossRef](#)]
13. Dong, J.; Yu, S.; Choi, K.; Jeon, M. A child-robot theater afterschool program can promote children's conceptualization of social robots' mental capacities and engagement in learning. *Front. Robot. AI* **2025**, *12*, 1529421. [[CrossRef](#)]
14. Belpaeme, T.; Vogt, P.; Van Den Berghe, R.; Bergmann, K.; Göksun, T.; De Haas, M.; Kanero, J.; Kennedy, J.; Küntay, A.C.; Oudgenoeg-Paz, O.; et al. Guidelines for Designing Social Robots as Second Language Tutors. *Int. J. Soc. Robot.* **2018**, *10*, 325–341. [[CrossRef](#)]
15. Catlin, D.; Kandlhofer, M.; Cabibihan, J.-J.; Angel-Fernandez, J.; Holmquist, S.; Csizmadia, A.P. EduRobot Taxonomy. In *Smart Learning with Educational Robotics*; Springer International Publishing: Cham, Switzerland, 2019; pp. 333–338. [[CrossRef](#)]
16. Pai, R.Y.; Shetty, A.; Dinesh, T.K.; Shetty, A.D.; Pillai, N. Effectiveness of social robots as a tutoring and learning companion: A bibliometric analysis. *Cogent Bus. Manag.* **2024**, *11*, 2299075. [[CrossRef](#)]
17. Belpaeme, T.; Baxter, P.; De Greeff, J.; Kennedy, J.; Read, R.; Looije, R.; Neerinx, M.; Baroni, I.; Zelati, M.C. Child-Robot Interaction: Perspectives and Challenges. In *Social Robotics*; Herrmann, G., Pearson, M.J., Lenz, A., Bremner, P., Spiers, A., Leonards, U., Eds.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2013; Volume 8239, pp. 452–459. [[CrossRef](#)]
18. Mubin, O.; Stevens, C.J.; Shahid, S.; Mahmud, A.A.; Dong, J.-J. A Review of the Applicability of Robots in Education. *Technol. Educ. Learn.* **2013**, *1*, 13. [[CrossRef](#)]
19. Löffler, D.; Schmidt, N.; Tscharn, R. Multimodal Expression of Artificial Emotion in Social Robots Using Color, Motion and Sound. In *Proceedings of the 2018 ACM/IEEE International Conference on Human-Robot Interaction*; ACM: Chicago, IL, USA, 2018; pp. 334–343. [[CrossRef](#)]
20. Little, A.W. Multigrade teaching: Towards an international research and policy agenda. *Int. J. Educ. Dev.* **2001**, *21*, 481–497. [[CrossRef](#)]
21. González-Oliveras, P.; Engwall, O.; Wilde, A. Social Educational Robotics and Learning Analytics: A Scoping Review of an Emerging Field. *Int. J. Soc. Robot.* **2025**, *17*, 1113–1128. [[CrossRef](#)]
22. Cano, S.; Díaz-Arancibia, J.; Arango-López, J.; Libreros, J.E.; García, M. Design Path for a Social Robot for Emotional Communication for Children with Autism Spectrum Disorder (ASD). *Sensors* **2023**, *23*, 5291. [[CrossRef](#)] [[PubMed](#)]
23. Tengler, K.; Kastner-Hauler, O.; Sabitzer, B. Identifying Preliminary Design Principles for a Robotics-based Learning Environment. In *Proceedings of the 2021 16th International Conference on Computer Science & Education (ICCSE)*; IEEE: Lancaster, UK, 2021; pp. 771–776.
24. Hoeft, R.M.; Mentis, H.M. Beyond User-Centered Design: Applicable Concepts from Complementary Approaches. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2009**, *53*, 1844–1848. [[CrossRef](#)]
25. Davis, P.M.; Class, M. Educational Robots for Social and Emotional Learning. *AI Comput. Sci. Robot. Technol.* **2023**, *2*, 1–10. [[CrossRef](#)]
26. Alves-Oliveira, P.; Arriaga, P.; Paiva, A.; Hoffman, G. Guide to build YOLO, a creativity-stimulating robot for children. *HardwareX* **2019**, *6*, e00074. [[CrossRef](#)]
27. Hung, I.-C.; Chao, K.-J.; Lee, L.; Chen, N.-S. Designing a robot teaching assistant for enhancing and sustaining learning motivation. *Interact. Learn. Environ.* **2013**, *21*, 156–171. [[CrossRef](#)]
28. Tanaka, F.; Cicourel, A.; Movellan, J.R. Socialization between toddlers and robots at an early childhood education center. *Proc. Natl. Acad. Sci. USA* **2007**, *104*, 17954–17958. [[CrossRef](#)]
29. Leite, I.; Martinho, C.; Pereira, A.; Paiva, A. As Time goes by: Long-term evaluation of social presence in robotic companions. In *Proceedings of the RO-MAN 2009—The 18th IEEE International Symposium on Robot and Human Interactive Communication*; IEEE: Toyama, Japan, 2009; pp. 669–674.
30. Souza, A.; Sousa, C.E.; Torres, D.; Paradedá, R. Roboldo: An Affective Robot for Empathetic Social Interactions in Education. In *Proceedings of the 2024 Brazilian Symposium on Robotics (SBR), and 2024 Workshop on Robotics in Education (WRE)*; IEEE: Goiania, Brazil, 2024; pp. 307–312.

31. Ali, M.; Cheema, S.M.; Ayub, N.; Naz, A.; Aslam, Z. Impact of Adopting Robots as Teachers: A Review Study. In Proceedings of the 2022 International Conference on Emerging Technologies in Electronics, Computing and Communication (ICETECC); IEEE: Jamshoro, Pakistan, 2022; pp. 1–9.
32. Bredder, E.; Lilly, S.; Wilkens, K.; Vieira, C. Low-cost Educational Robotics (LCER) Design Framework. In Proceedings of the 2025 ASEE Annual Conference & Exposition Proceedings; ASEE Conferences: Montreal, QC, Canada, 2025; p. 56945.
33. Chiou, A.; Lye, N.C.; Lai, R.; Wong, K.W. Framework for robotics in education: Some experiences and case studies in test arena based projects. In Proceedings of the 2011 5th IEEE International Conference on E-Learning in Industrial Electronics (ICELIE); IEEE: Melbourne, Australia, 2011; pp. 28–33.
34. Demetroulis, E.A.; Papadogiannis, I.; Wallace, M.; Pouloupoulos, V.; Antoniou, A. CORE: Cultivation of Collaboration Skills via Educational Robotics. *Knowledge* **2025**, *5*, 9. [[CrossRef](#)]
35. Oh, K.; Kim, M. Social attributes of robotic products: Observation of child-robot interaction in school environment. *Int. J. Des.* **2010**, *4*, 45–55.
36. Universal Design for Learning Guidelines Version 2.2. Available online: <https://udlguidelines.cast.org/> (accessed on 23 January 2026).
37. Charisi, V.; Davison, D.; Reidsma, D.; Evers, V. Evaluation methods for user-centered child-robot interaction. In Proceedings of the 2016 25th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN); IEEE: New York, NY, USA, 2016; pp. 545–550.
38. Paiva, A.; Leite, I.; Boukricha, H.; Wachsmuth, I. Empathy in Virtual Agents and Robots: A Survey. *ACM Trans. Interact. Intell. Syst.* **2017**, *7*, 11. [[CrossRef](#)]
39. The Design-Based Research Collective. Design-Based Research: An Emerging Paradigm for Educational Inquiry. *Educ. Res.* **2003**, *32*, 5–8. [[CrossRef](#)]
40. Grier, R.A.; Bangor, A.; Kortum, P.; Peres, S.C. The System Usability Scale: Beyond Standard Usability Testing. *Proc. Hum. Factors Ergon. Soc. Annu. Meet.* **2013**, *57*, 187–191. [[CrossRef](#)]
41. Schrepp, M.; Hinderks, A.; Thomaschewski, J. Applying the User Experience Questionnaire (UEQ) in Different Evaluation Scenarios. In *Design, User Experience, and Usability. Theories, Methods, and Tools for Designing the User Experience*; Marcus, A., Ed.; Lecture Notes in Computer Science; Springer International Publishing: Cham, Switzerland, 2014; Volume 8517, pp. 383–392.
42. Lewis, J.R. The System Usability Scale: Past, Present, and Future. *Int. J. Hum.–Comput. Interact.* **2018**, *34*, 577–590. [[CrossRef](#)]
43. Laugwitz, B.; Held, T.; Schrepp, M. Construction and Evaluation of a User Experience Questionnaire. In *HCI and Usability for Education and Work*; Holzinger, A., Ed.; Lecture Notes in Computer Science; Springer: Berlin/Heidelberg, Germany, 2008; Volume 5298, pp. 63–76.

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