Research Topics

# STEM: innovation on teaching and learning

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# STEM: innovation on teaching and learning

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# Table of contents

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# Editorial: STEM: innovation on teaching and learning

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KEYWORDS

**STEM education, technology, assessment, pre-service teachers, innovative teaching**

Editorial on the Research Topic
STEM: innovation on teaching and learning

This Research Topic centers on Science, Technology, Engineering, and Mathematics (STEM) education, a model that inspires extensive studies on innovative teaching and learning approaches. Given STEM's alignment with the development of 21st century skills, there is a growing need for additional research to deepen our understanding and improve the application of this model, in formal, non-formal, and informal education.

To address these needs, this Research Topic assembles high-quality studies that focus on STEM education, encompassing both teacher training and students' engagement across educational stages. It aimed to include a broad spectrum of research areas that support effective STEM implementation in classrooms and provide valuable insights into STEM focused educational training experiences. The 10 articles cover a variety of approaches, both qualitative and quantitative, with different types of studies (empirical research, research-action, training, exploration), from five continents and 16 countries. They are organized in four areas, according to the subject or context.

## Teacher concerns in STEM education

Evagorou explores how pre-service kindergarten teachers understand and implement STEM education, in a Science Methods Course for Kindergarten. Findings revealed that they were initially unfamiliar with STEM and highlights the need for teacher preparation programs on STEM knowledge and lesson implementation skills. Zhumabay et al. examine the impact of a STEM education course on teachers' self-efficacy and experiences. Data from mathematics master's candidates showed a significant increase in self-efficacy in teaching STEM, with positive feedback on course content, activities, and assignments. Their findings provide insights into designing effective STEM courses and offer practical implications for course development. Lai and Cheng advocate the introduction of engineering into primary science classroom, presenting an innovative pedagogy: the STEM × Play program. Authors study about students' perceptions and attitudes toward learning STEM and teachers' perception of teaching STEM. Results showed students developed skills essential for STEM jobs and its inclusion in the community of practice was important for improving teachers' STEM skills.

## Integration of educational technology

Rodríguez investigates the effectiveness and challenges of creating Virtual Reality (VR) based teaching sequences using interactive tools such as Neotrie, with pre-service teachers. The study showed that the integration of VR environments provided teachers a great deal of freedom and flexibility to create VR scenes themselves. Nevrelova et al. analyze the impacts and benefits of Augmented Reality, specifically of Quiver application, as an educational tool in primary school. The conclusions emphasize that the use of this type of application promotes the development of digital literacy of the students, while promoting engagement, motivation and collaborative communication. Debrenti evaluates the effectiveness of game-based learning, comparing the impact of digital and non-digital games on student engagement and learning, in elementary school (9–11 years). The results showed that digital games often led to better student performance, especially in tasks that required logical thinking, while non-digital games offered valuable opportunities for hands-on learning and social interaction. Both modalities should be strategically integrated into math's teaching to address different learning needs and objectives.

## Developments in higher education

Fehér et al. investigate the use of propositional logic among university students in different study programs. They found significant differences according to gender, age, type of secondary school leaving exam and parents' highest education level. Mathematics-informatics students achieved the best results, followed by engineering, economics, education, sciences, and humanities students. They also demonstrated that students performed differently in three selected areas of formal logic, with the lowest performance on statement negation tasks. Debrenti and Bordás focus on logical basic knowledge and operations in everyday life, mathematical, physical, chemical, and biological contexts, in a western region of Romania. Their main results showed that daily life problems were solved correctly by the highest percentage of students, followed by problems in biological, physical, and mathematical context. Students were least successful in logical problems related to chemistry. Thus, authors state that semantic content must be considered. Armenta and Dominguez analyze interdisciplinary experiences of twelve university students in a calculus course through three categories: (i) what students think about interdisciplinarity, (ii) how they act when being involved in integrations, and (iii) what external factors are involved in shaping their experience. This work contributes to the understanding of educational interdisciplinary practices in a student-centered perspective, providing empirical evidence of interdisciplinary engagement in a calculus course.

## Assessment strategies

Hanauer et al. present a course-based research pedagogy enrolling students in authentic research to enhance learning and persistence in science. A model for assessing students was developed, focusing on four aims: (1) assessing laboratory work and scientific thinking, (2) evaluating mastery of concepts and skills, (3) appraising scientific communication, and (4) fostering metacognition. This model balances feedback and grading to support student engagement without undermining the goals of course-based research education.

The studies in this Research Topic emphasize the actual relevance of STEM Education, highlighting further innovative and interdisciplinary approaches to STEM. Furthermore, it addresses how STEM education relates to the development of 21st century skills, challenges and opportunities. To this end, it is mandatory to continue prioritizing teachers (initial and continuing) training, as well as using inclusive practices in STEM education.

By addressing diverse contexts and using multiple theoretical frameworks, these studies can provide a solid foundation for future research and practice in the STEM Education. We hope that these contributions encourage more innovation and collaboration for STEM Education, necessary to develop innovative solutions to complex and really problems and build a more sustainable and equitable future.

## Author contributions

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# Students' propositional logic thinking in higher education from the perspective of disciplines

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Logic and logical thinking are present and play an important role in most of the disciplines at the university level but in different ways. In our research, which has been ongoing for several years, we are investigating the use of propositional logic among university students in different study programmes. Our current study evaluated data from 1,429 respondents involving students from 15 universities. The non-standardised knowledge test was previously pilot-tested and consisted of 15 tasks from selected elements of propositional logic in a different natural science subject-specific context. Significant differences in average results were found in terms of students' gender, age, type of secondary school leaving exam and parents' highest education level. Our research mainly aimed to compare students' test scores by students' fields of study. On average, mathematics-informatics students had the highest success rate of 67.4%, compared to students in engineering (61.0%), economics (57.9%), education (56.6%), science (56.5%) and humanities (54.7%). The result is significant ($F$ = 13.521, $p$-value < 0.001). Furthermore, we found that the students performed differently in three selected areas of formal logic ($F$ = 1108, $df$ = 2, $p$ < 0.001), with the lowest performance on statement negation tasks. The difference in means across groups of tasks is significant by the gender of the students and by their secondary education level.

KEYWORDS

**propositional logic, logical thinking, scientific tasks, fields of study, university students**

## 1. Introduction

The tools of logic, or at least elements or parts of them, are used in practically all disciplines, from the natural sciences to the social sciences, economics or law. Logic is the science of clear and consistent thinking, which no discipline can do without, and in stating and proving its propositions, all disciplines, whether deliberately or by instinct, take logical steps and apply the rules of logic.

In an academic study in every age, the study of logic and its role in use has been of fundamental importance. Logic as a research discipline saw its greatest leap of development in the first half of the twentieth century, but with all that progress in research, its relative importance in the teaching portfolio of the academy has diminished. What is the reason for this? According to Restall (2015), the reason for this is greater specialisation and differentiation and excessive learning. Due to this phenomenon, students avoid taking it even if a university offers logic as a subject. Restall declares this phenomenon as a cultural problem. "*The research culture of logic - the kind of work it produces - seems radically alien to that of its elsewhere academic disciplines*" (Restall, 2015).

The disciplines have different aims, values and traditions. They have different questions to ask and problems to solve. They also have different techniques and tools to apply. How does this reflect on the knowledge of the current generation of students studying in various fields of disciplines? To understand the differences between the disciplines, one needs to understand the features of disciplines. While the science disciplines aim to give an objective view and third-person descriptions of the world, many branches of the sciences use prediction and testing of hypotheses based on observation and theory development. Different things need to occur in the humanities. The humanities are not just about an objective reality to be described from the perspective of the independent observer (third-person) view. Expressive elements, viewed from the first-person, involve agency and subjectivity at their core humanities. It does not mean that the sciences do not involve creativity or agency. The engineering discipline aims to solve problems involving our actions in the world around us (Restall, 2015).

## 2. Theoretical background

Propositional logic is the simplest of the classical logical questions. According to Klement (2004) definition propositional logic *"is the branch of logic that studies ways of joining and/or modifying entire propositions, statements or sentences to form more complicated propositions, statements or sentences, as well as the logical relationships and properties that are derived from these methods of combining or altering statements."*

Propositional logic can be applied in many areas of life and science, including decision making, problem solving, developing critical thinking, improving communication by making arguments and information analysis by evaluating the truth or falsity of information. Logic is generally concerned with statements in natural language and the conclusions that can be drawn from them. Propositional logic is concerned with statements and the basic logical operations, or logical connections that link them. It plays a significant role in many areas where rigorous analysis and evaluation of claims and arguments is required and integrates reasoning and thinking skills into our everyday lives. In the Stanford Encyclopaedia of Philosophy, the concept of propositional logic is defined as "*the study of the meanings of, and the inferential relationships that hold among, sentences based on the role that a specific class of logical operators called the propositional connectives have in determining those sentences' truth or assertability conditions*" (Franks, 2023).

Since propositional logic is a broad area of mathematics, we focussed our research on three elements: quantifiers, negations, inferences. The main elements of the language of mathematics are quantifiers, which are designated as either universal or existential. According to Saban (2014) quantifiers have an undeniable importance in giving meaning to mathematical information. Furthermore, the ability to deal with quantifiers is vital not just for obtaining mathematical knowledge, but also for efficiently exploiting mathematics' diverse conceptual frameworks (Dubinsky et al., 1998). It is known that students receiving secondary education and university education experience considerable difficulties in understanding quantifiers (Dubinsky and Yiparaki, 2000). Negation is the most basic logical connective (logical operator), which states the falsity of a proposition and, unlike negations and other emphases in natural language, does not indicate the cause of the falsity. As defined by Mosley and Baltazar (2019) "*negations are compound propositions formed from a simpler proposition.*" In everyday life and in formal systems, logic is also the study of the forms of correct inference. According to Mosley and Baltazar (2019), people are naturally and usually logical; whether a person is educated or not is irrelevant. Inference, as they put it "*is the process by which the truth of one proposition (the conclusion) is affirmed on the basis of the truth of one or more other propositions that serve as its premise or premises*" (Mosley and Baltazar, 2019). According to another author, Kumar (2017) "*an inference is a conclusion that a person can draw from certain observed or supposed facts.*"

Developing logical thinking and reasoning skills is one of the main goals of science learning. Logical thinking is a process of thinking logically, rationally and reasonably (Lazear, 2004; Yaman, 2015). One of science learning objectives is to empower students' logical thinking abilities (Parmin et al., 2017), and this ability is needed by each individual in order to be able to solve a variety of complex problems (Sezen and Bülbül, 2011). Logical thinking is also associated with the function of all senses and processed information, which means that students can distinguish, criticise, and process knowledge in words based on phenomena through logical thinking. Therefore, they can discover the answer to each problem. Practicum work in science learning is a problem-solving method which also requires logical thinking abilities (Hibbard, 2000). Logical thinking ability connects the science concept with students' knowledge and experience so that students can solve complex problems (Pezzuti et al., 2014). In Taber (2017) view science is often associated with logical thinking, and this is indeed an important feature of science, because "*logic is needed to work out predictions consistent with particular hypotheses or models, and logic is needed to interpret data in terms of different principles, laws and theories, and to construct arguments to persuade other scientists of the validity of conclusions.*"

According to Bakır et al. (2015), four factors have influenced how humans create knowledge: language skills, logical thinking ability, experience, and interest. With logical thinking, the students solve the problem by conducting various mental practices or reaching principles or rules by executing some abstraction and generalisation. The students' conceptions from useful prior knowledge can build on (Titler, 2002) with logical thinking abilities that should be given new emphasis in science teaching and learning (Fah, 2009). Students who do not have the mental structures for conditioned reasoning may have difficulties acquiring knowledge in science. Also, if the reasoning is a filter between experience and mental schemas, then it is evident that students who cannot use conditional reasoning operations perform worse in science (Piburn, 1980). Low scientific reasoning skills can be discussed in the current education system. Lay (2010) points out that the education system influences logical thinking abilities, particularly in a system that places more importance on examination results. Other authors suggest that improving logical reasoning skills as part of higher-order thinking skills is an important objective of education (Zohar and Dori, 2003).

Piburn and Baker (1988) researched to examine the relationship between logical reasoning ability and school science grades. According to the results obtained by the Propositional Logic Test and Test of Logical Reasoning, correlations of grades in science with the PLT (0.57) and the TOLT (0.63) were high. Pallrand et al. (1981) researched a sample of nearly 2,000 undergraduate students oriented toward the ability to use formal logic. The results showed systematic and consistent errors in students' interpretations of logical propositions. The study pointed to a specific misunderstanding of the meaning of a conditional statement, an inconsistent use of truth tables, an error in contraposition, and the use of tautology, in which all choices are seen as correct.

According to Kumar (2017), studying formal logic helps improve the thinking process and tries to refine and improve the thinking ability. The objectives of Kumar's study are to know the effectiveness of formal logic courses and to determine the critical thinking variables that are effective and that are ineffective. The analysis revealed no significant relationship between critical thinking variables and formal logic courses. Riyanti et al. (2019) examined the relationship between logical-thinking ability and students' science achievement. The results show an insignificant relationship between logical-thinking ability and students' science achievement. The results of the pre-test and post-test evaluation of the formal logic course indicate to be sensitive enough to detect a positive effect on students' critical thinking and problem-solving skills. Making decisions based on mindset and cognitive knowledge is an important skill in logical thinking ability (Pezzuti et al., 2014; Seyhan, 2015).

Propositional logic and logical reasoning are present and play an important role in both the natural and social sciences. The various tools and elements of logic are used in practically every discipline. It is therefore necessary to pay adequate attention to the preparation of students of different study programmes in propositional reasoning during their university studies. The purpose of our research was to reveal the differences in the application of propositional logic knowledge of university students. The main research questions were to (1) examine and assess the knowledge of the basic elements of propositional logic and logical reasoning and to compare the students' performance within different scientific disciplines. In addition we wanted to (2) investigate the background variables by means of which significant differences can be detected between the various groups of students and (3) compare students' performance in the selected areas of propositional logic.

## 3. Materials and methods

The main objective of our research was to examine and compare the results of a knowledge test of formal logic tasks concerning the students' scientific discipline based on their study programme. The survey participants were students from Central European universities studying in Hungarian language. Students from 15 universities participated in the research; most participants were from Slovakia, 511 (35.8%), 404 (28.3%) from Hungary, 363 (25.4%) from Romania, 138 (9.7%) from Serbia and 13 (0.9%) from Ukraine. A total of 1,505 students completed the online test. After data validation, 1,429 respondents were included in the study. The study sample included 528 (37.0%) men and 899 (63.0%) women, and mostly (1211, 84.9%) from the age group 18–25 years. The sample is not representative.

Students were categorised into six scientific disciplines based on their study programme. The largest proportion of students in the sample are paedagogical students (500, 35.0%), which includes students studying pre-primary education and teacher education. In addition, 401 (28.1%) students are studying economics, 178 (12.5%) are studying mathematics or computer science, 151 (10.6%) are studying engineering, 121 (8.5%) are studying humanities and 78 (5.5%) are studying various natural sciences. The sociodemographic characteristics of the participants are reported in **Table 1**.

The results of the respondents were also analysed according to the highest educational level of the parent (**Table 2**).

As a research tool, a non-standardised, previously pilot-tested knowledge test was used, which consisted of 15 tasks from selected elements of propositional logic. These tasks were placed in different natural sciences subject-specific content: physics, chemistry, biology and also mathematics, and context from everyday life. The tasks were divided into three groups considering the three selected propositional logic topics. The first group (A) included five tasks on understanding quantifiers, five tasks in the second group (B) used negation of statements, and another five tasks (C) dealt with a formulation of inferences. The test includes tasks on universal and existential quantifiers, and uses the terms of *at least*, *at most*. The tasks contain the logical operators *and*, *or*, the correct interpretation of which is important for the solution. The test is available in the Appendix. Except for one biology task, the test included multiple-choice tasks with one correct answer. Each of

TABLE 1 Demographic characteristics of the sample ($N$ = 1429).

| Characteristics | *n* | Valid% |
|---|---|---|
| Gender | | |
| Men | 528 | 37.0 |
| Women | 899 | 63.0 |
| Age | | |
| 18–25 | 1211 | 84.9 |
| >25 | 216 | 15.1 |
| Scientific discipline | | |
| Mathematics/informatics | 178 | 12.5 |
| Engineering | 151 | 10.6 |
| Economics | 401 | 28.1 |
| Natural sciences | 78 | 5.5 |
| Paedagogy | 500 | 35.0 |
| Human sciences | 121 | 8.5 |
| Type of secondary school | | |
| Secondary grammar school | 735 | 51.5 |
| Secondary school | 693 | 48.5 |

TABLE 2 Parents' highest education level.

| Characteristics | Father | | Mother | |
|---|---|---|---|---|
| | *n* | Valid% | *n* | Valid% |
| Primary school | 126 | 8.9 | 151 | 10.7 |
| Secondary school without an exam | 478 | 33.9 | 333 | 23.5 |
| Secondary school with an exam | 571 | 40.5 | 633 | 44.7 |
| Higher education | 236 | 16.7 | 299 | 21.1 |

the 15 logic tasks in the test was worth 1 point for a correct answer and 0 points for a wrong answer.

The survey was performed online using Google Forms, involving each partner university. The test was disseminated with the cooperation of university lecturers. Students received the Google Form link to the test directly from their teachers during the lectures, and they solved the questions under their personal supervision. Data collection was carried out during the winter semester of 2022. The final database, including the data of 1,505 respondents, was downloaded from Google Forms as a Microsoft Excel sheet. The data were further examined and analysed in IBM SPSS Statistics version 27.0.

Numerical data were summarised as means and standard deviations, and categorical data were presented as frequencies and proportions. The Shapiro–Wilk test was performed to evaluate variable distribution. Since the sample size is sufficiently large, we used statistical parametric tests, which assume normal distribution of the variable. One-way ANOVA was employed to compare score distributions by task-groups and the tasks′ subject-specific context. Independent samples *t*-test was used to compare means of continuous variables between two groups. The test results were statistically significant for a *p*-value less than 0.05.

## 4. Results

When analysing the data, the test score was calculated, and the success rate as a percentage of the maximum score for each respondent. Students' scores were analysed and compared according to each background variable for the evaluation. We also compared results on the entire set of tasks and the three task-groups from the disciplines′ perspective. The variable "score" is not normally distributed according to the Shapiro-Wilk test ($W = 0.983$, $p < 0.001$). The SW test indicates that the data are not normal, and skewness and kurtosis are larger than their 1.96 standard errors (2.06 and 2.69, respectively). According to recent studies (Orcan, 2020) Mann-Whitney *U*-tests or other non-parametric tests should be used to test mean differences. On the other hand the sample size is sufficiently high ($N = 1429$), therefore we can use statistical methods assuming normal distribution of variables.

The respondents' average test score was 8.79 (SD = 2.58), 95% confidence interval is 8.66–8.92. The overall correct answer rate was 58.6%. The median value was nine points. Significant differences in average test scores were found regarding students' gender, age, type of secondary school leaving exam and the parents' highest education level (Table 3).

TABLE 3 Comparison of the respondents' results.

| Characteristics | Mean | SD | Test stat | *p*-value |
|---|---|---|---|---|
| **Gender** | | | | |
| Men | 9.19 | 2.64 | 4.428[a] | <0.001 |
| Women | 8.56 | 2.51 | | |
| **Age** | | | | |
| 18–25 | 8.73 | 2.58 | −2.080[a] | 0.038 |
| >25 | 9.13 | 2.57 | | |
| **Type of secondary school** | | | | |
| Secondary grammar school | 9.14 | 2.53 | 5.401[a] | <0.001 |
| Secondary school | 8.41 | 2.58 | | |
| **Highest education level/father** | | | | |
| Primary school | 8.35 | 2.42 | 5.475[b] | 0.001 |
| Secondary school without an exam | 8.72 | 2.55 | | |
| Secondary school with an exam | 8.71 | 2.53 | | |
| Higher education | 9.36 | 2.74 | | |
| **Highest education level/mother** | | | | |
| Primary school | 8.07 | 2.41 | 9.632[b] | <0.001 |
| Secondary school without an exam | 8.49 | 2.55 | | |
| Secondary school with an exam | 8.91 | 2.58 | | |
| Higher education | 9.28 | 2.55 | | |

[a]Independent samples *t*-test (t). [b]One-Way ANOVA (F).

The sample included 528 (37.0%) men and 899 (63.0%) women. Men scored significantly better with 9.19 points compared to women with 8.56 points. Students aged 18–25 years achieved an 8.73 average score, which is significantly lower than those over 25 years (9.13). According to the type of secondary school, students who finished grammar school achieved significantly better results in average total score (9.14) compared to the students who finished other types of secondary school (8.41). The results also show that the parents' educational level impacts the score. The best results were achieved by students whose parents had a higher education. Considering the father's education, the students' highest score was in the group with higher education (9.36), and in the case of the mother's higher education, it was 9.28 points. Students with higher scores were those whose parents had higher education degrees.

### 4.1. Students' results in the perspective of disciplines

The main objective of our research is to assess the knowledge of the basic elements of propositional logic and logical reasoning and to compare the students' results within different scientific disciplines. Accordingly, we compared the test scores of respondents by their discipline. Significant differences in average test scores were found regarding students' discipline ($F = 13.521$, $p < 0.001$). The mathematics or computer science students achieved the highest average score of 10.11, with a 67.4% success rate. Next in order are engineering students (61.0%), economics students (57.9%), students studying paedagogical sciences (56.6%), natural sciences (56.55) and finally, human sciences (54.7%). Test score distributions by the students' disciplines are shown in **Figure 1**.

The ANOVA *post hoc* pairwise comparison between group means with *t*-test shows which means differ. There are 15 pairings in total, comparing each of the 6 disciplines. When paired with all 5 majors, the mathematics/informatics group score shows a significant difference in means. The means for the groups of engineering, economics, natural sciences, and paedagogy students are at the same level (with no significant difference). Students of human sciences achieved the lowest score.

Significant differences were found ($F = 1108$, df = 2, $p < 0.001$) comparing the mean score in three task-groups with the tasks on quantifiers (3.48), negation (1.73), inferences (3.58). The lowest average score (1.73) was achieved in task-group B on statement negation. *Post hoc* analysis shows the different pairwise distributions for groups A–B, B–C, and A–C. We conducted independent samples *t*-tests to compare averages separately for each group of tasks (**Table 4**). The results show that the differences in mean score are significant in all task-groups, according to the gender of the students, with men scoring higher in all three task-groups. The average score in the age group over 25 years is higher in all three groups A, B, and C, but: based on the *t*-tests, there is a significant difference only in task-group C-inferences (**Table 4**). As we can see in **Table 4**, the mean score is higher for students who graduated from secondary grammar school compared to students from other types of secondary schools. The *t*-tests indicate that the difference is statistically significant not only comparing the average score on the entire set of tasks but also in the three task-groups.

Analysing the students' results by disciplines (**Table 5**), the mathematics/informatics students performed best in all three groups of tasks. Humanities students performed the poorest in the logic tasks. They scored the lowest average in all three groups of tasks, and in the case of the paedagogy students, they were the worst in inferences by one hundredth of a point.

The results of the 15 propositional logic tasks were summarised in **Table 6** by indicating with a "+" sign the values when the students' scores by their discipline were higher than the overall average. The score below the average was marked with a "−" sign. The tasks were marked in each task group with the letters M (mathematics), P (physics), B (biology), Ch (chemistry), and EL (everyday life). As a result of this overview, we can find that mathematics/informatics students achieved the best results with 14 times above-average values. Engineering students obtained 11 above-average results. All other students by the disciplines scored below the average on more than half of the 15 tasks. Economics and natural sciences students got 6 + signs, paedagogy students 4 + signs, and respondents studying human sciences obtained 2 + signs for an above-average score.

**Table 6** also shows in which subjects or task contexts the students were successful in. The students majoring in mathematics or informatics performed above average in all five tasks in part A. Regarding engineering specialisations, 3, economics, natural science and paedagogy specialisations performed above average in 2 tasks, while students studying the humanities remained below average in all tasks. Most did not know task A4 (task no. 4 in task group A, subject: chemistry) with 58.5%; this also applies to each specialisation separately. A total of 18.4% of those who filled in completed all five tasks and achieved maximum points; this figure is 30.9% for mathematics or informatics specialisations.

In the case of task group B, the mathematics/informatics students performed above the average in all five tasks. Students with an engineering specialisation had above-average results in 4 questions, but in the economics, natural sciences and paedagogy specialisation, they scored above the average in only 1 question. Humanities students completed below average on all questions. Most did not know task B2 (question from everyday life) with 76.7%; this does not apply to the disciplines separately. The mathematics/informatics specialisations students made a mistake on question B3 (physics question), the engineering and paedagogy specialisations got B2 (a question from everyday life), and the economics, natural sciences and humanities specialisations got B4 (chemistry question) they knew the least. Those who solved all five tasks correctly are 2.4% of the total; for the mathematics/informatics students, this is 7.9%. Among those who filled in, 13.9% achieved 0 points in group B of questions; regarding specialisations, natural science students performed the worst (19.2%).

In the case of task group C, students majoring in mathematics or informatics performed the best (above average in 4 tasks), economics specialisation students performed above average in 3 questions, natural sciences and humanities students in 2 questions, and paedagogy students performed above average in only 1 question. Most (55.3%) incorrect answers were given for task C1 (chemistry question); this also applies separately to the majors. Mathematics or informatics specialisations performed below average on task C5 (biology). Evaluating the entire group, 28.3% of the sample solved all five tasks correctly; in the case of mathematics-informatics students, this was 41%. A total of 1.5% of those who filled in received 0 points; students with teacher specialisation finished last with 2%.

## 5. Discussion

Our research focussed on examining university students' logical thinking and knowledge of selected elements of propositional logic, considering their different fields of study. Based on the scores achieved, the students have significant differences in solving the tasks regarding the scientific disciplines by the student's study programme. The best results were achieved by students majoring in mathematics or computer science, while the worst results were achieved by students studying humanities.

Several studies have pointed out the correlation between formal logic and success in science. Mitchell and Lawson (1988) showed formal reasoning ability as an important determinant of the ability to solve genetic problems and interpret text material in biology. Chandran et al. (1987) pointed out that formal thinking is more influential in predicting achievement in chemistry than prior knowledge. Siváková et al. (2018) showed how to develop thinking

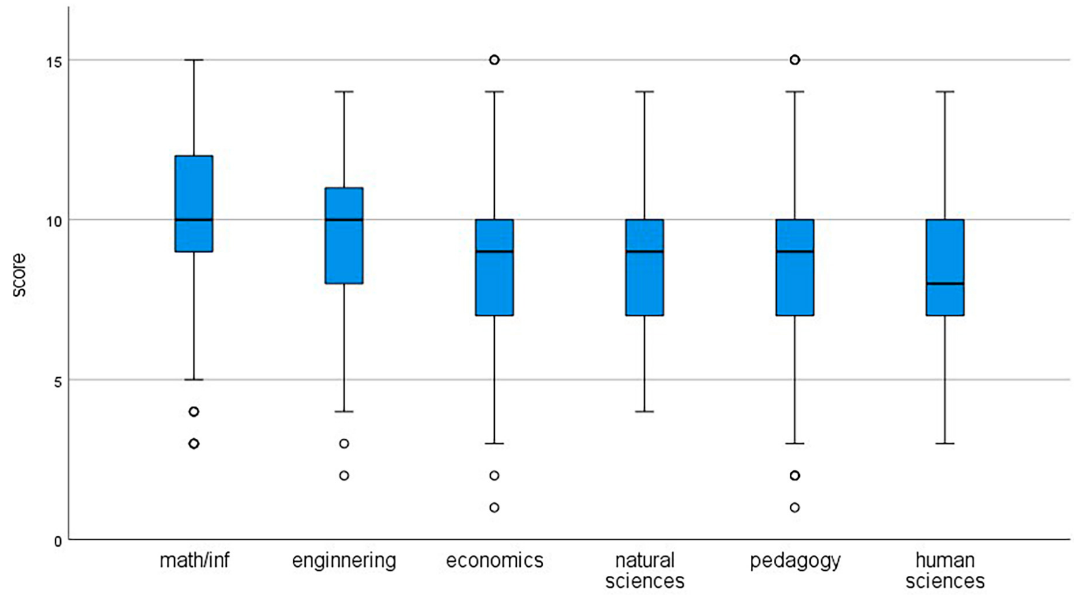


FIGURE 1
Test score distribution by the students disciplines.

skills in chemistry lessons. There were also correlations between physics achievement with inductive and deductive reasoning (Enyeart et al., 1980). The studies also showed that formal thinking and the ability to interpret logical connectives differ (Lawson et al., 1978; Lawson, 1983). The result of research conducted by Pallrand et al. (1981) showed that those students who are more successful in science are also those who can use formal logic and can use the rules of conditional reasoning in the correct way. Zulkipli (2020) in a study carried out to investigate scientific reasoning skills among science pre-service teachers. They found no significant relationship between the studied science disciplines and the scientific reasoning patterns of the science pre-service teachers.

We found a significant difference in test results according to gender, age group, the student's type of secondary school leaving exam and also according to the parent's education level. Our survey results show that men performed better on the propositional logic tasks in the three task groups. Several studies have examined gender differences related to mathematics learning compared to using variables including innate abilities, attitudes, motivation, talent and performance. The literature has recognised the relationship between gender and mathematics performance (Goodchild and Grevholm, 2009; Munroe, 2016; Lin et al., 2020) and concludes that there is a higher performance rate among males in mathematics than females. It is evident that there is a tendency for males to perform better on mathematics tests than females when it comes to learning mathematics, and according to Arnup et al. (2013), these discrepancies might be partly explained by the differences in the cognitive styles of the individuals. Vos et al. (2023) examined which factors could cause gender differences in mathematical performance tests. Results showed that women scored significantly lower than men on the arithmetic and cognitive reflection tests. The results of Niwas (2018) research show that significant differences exist among low, average and high logical thinking on achievement in science in favour of high logical thinking for all groups (rural male, urban male, rural female and urban female) and the total sample.

Based on our results, students whose parents have a higher education achieved better results than those whose parents graduated from secondary or elementary school. According to our assumption, this may be related to the greater expectations and requirements of the parents during the student's entire schooling. However, it may also play a role that the parents who have graduated from the university can support their child to a greater extent in learning, mastering and understanding the curriculum, and being a positive example. They also serve in the children's further education and can take a more significant part in the financial support of their studies.

Most literature sources show that parents' educational level strongly influences educational and economic opportunities for their children (Dubow et al., 2009; Kalil et al., 2012; Benner et al., 2016). Several researchers say parental education is an important predictor of children's educational and behavioural outcomes (Dearing et al., 2001; Davis-Kean, 2005). A study by Davis-Kean (2005) examined how socioeconomic status, specifically parents' education and income, indirectly relates to children's academic achievement through parents' beliefs and behaviours. The author found that the socioeconomic factors were related indirectly to children's academic achievement through parents' beliefs and behaviours.

A meta-analysis by Sirin (2005) reviewed the literature on socioeconomic status and academic achievement in journal articles published between 1990 and 2000. The results showed a medium to strong socioeconomic status–achievement relation and that factors such as parental occupation, education and income are strongly related to student academic outcomes. Some other studies have also investigated the relationship between parental education and students' overall academic achievements. All these studies

TABLE 4 Test results by logic elements.

| Characteristics | Mean | SD | Test stat (t) | *p*-value |
|---|---|---|---|---|
| Quantifiers | | | | |
| **Gender** | | | | |
| Men | 3.58 | 1.05 | 2.677 | 0.008 |
| Women | 3.42 | 1.09 | | |
| **Age** | | | | |
| 18–25 | 3.47 | 1.08 | −1.009 | 0.313 |
| >25 | 3.55 | 1.11 | | |
| **Type of secondary school** | | | | |
| Secondary grammar school | 3.58 | 1.05 | 3.691 | <0.001 |
| Secondary school | 3.37 | 1.10 | | |
| Negation | | | | |
| **Gender** | | | | |
| Men | 1.85 | 1.29 | 2.705 | 0.007 |
| Women | 1.66 | 1.12 | | |
| **Age** | | | | |
| 18–25 | 1.72 | 1.17 | −0.688 | 0.492 |
| >25 | 1.79 | 1.31 | | |
| **Type of secondary school** | | | | |
| Secondary grammar school | 1.84 | 1.22 | 3.562 | <0.001 |
| Secondary school | 1.62 | 1.14 | | |
| Inferences | | | | |
| **Gender** | | | | |
| Men | 3.76 | 1.27 | 4.060 | <0.001 |
| Women | 3.48 | 1.26 | | |
| **Age** | | | | |
| 18–25 | 3.55 | 1.28 | −2.866 | 0.004 |
| >25 | 3.80 | 1.16 | | |
| **Type of secondary school** | | | | |
| Secondary grammar school | 3.73 | 1.25 | 4.445 | <0.001 |
| Secondary school | 3.43 | 1.27 | | |

consistently show that parental education is an important variable for predicting academic achievement (Terfassa, 2018); moreover, father's and mother's high education positively contributes to their children's academic achievement (Idris et al., 2020). Parents with higher educational attainment can explain the difference in children's achievement and attach more importance and value to education than parents with lower formal education and can provide activities that stimulate and promote children's cognitive and intellectual development (Şengönül, 2022).

The studies above showed a relationship between parental education and students' academic achievements. Research results are also indicating a positive relationship between mathematics achievement. Students whose parents were university-educated performed about two-thirds of a proficiency level higher than those whose parents had no more than a high school education (Education Matters, 2004). Moreover, students whose parents worked in an occupation that required advanced mathematics skills performed almost one proficiency level higher than students whose parents had similar education levels but whose occupations did not require advanced mathematics. Schreiber (2002) examined

TABLE 5 Evaluation of task-groups by disciplines.

| | Mean (SD) | | |
|---|---|---|---|
| Discipline | Quantifiers | Negation | Inferences |
| Mathematics/ informatics | 3.87 (1.05) | 2.30 (1.33) | 3.94 (1.20) |
| Engineering | 3.62 (0.98) | 1.72 (1.19) | 3.81 (1.26) |
| Economics | 3.45 (1.03) | 1.69 (1.18) | 3.55 (1.24) |
| Natural sciences | 3.33 (0.99) | 1.56 (1.16) | 3.58 (1.18) |
| Paedagogy | 3.41 (1.12) | 1.63 (1.11) | 3.45 (1.31) |
| Human sciences | 3.18 (1.16) | 1.55 (1.10) | 3.46 (1.23) |

TABLE 6 Evaluation of tasks by disciplines.

| Discipline | Quantifiers (A) | | | | | Negation (B) | | | | | Inferences (C) | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | M | P | B | Ch | EL | M | P | B | Ch | EL | M | P | B | Ch | EL |
| Mathematics/ informatics | + | + | + | + | + | + | + | + | + | + | + | + | – | + | + |
| Engineering | + | + | – | + | – | + | – | + | + | + | + | + | + | + | – |
| Economics | – | + | – | – | + | – | + | – | – | – | + | + | – | – | + |
| Natural sciences | – | – | + | – | + | – | + | – | – | – | – | – | + | + | + |
| Paedagogy | – | – | + | + | – | – | – | – | + | – | – | – | – | – | + |
| Human sciences | – | – | – | – | – | – | – | – | – | – | – | – | – | + | + |

advanced mathematics achievement with 1,839 students from 162 schools, and it was stated that parental education levels positively affected students' success in mathematics achievement.

The results of our survey show that there are also differences in the results of task groups A (quantifiers), B (negation), and C (inferences), which shed light on which propositional logic tasks are problematic for students. Examining the three selected areas of propositional logic, understanding and defining negations proved to be the most difficult. According to our experience, statements of this kind often cause problems for students during their studies, which can even be traced back to incorrectly interpreted logical connections in primary school but are often caused by expressions misused in everyday life. Most students have trouble interpreting the terms "at least" and "at most," and as a result, they cannot correctly define the negation of such statements either. According to one example of this faulty thinking, the negation of "at most" is "at least," which is not true on the set of integers. In the survey, we also noticed that many people responded to the denial of the "true for all $x$" type statement with the statement "not true for any $x$," obviously incorrectly.

We also found that secondary grammar school graduates achieved significantly better results than those who finished other types of secondary school. Similar results were shown in research conducted by Végh and Gubo (2022), which focussed on measuring computer science students' algorithmic and logical thinking skills. The results show that university students participating in the research who had a subject with similar content in secondary school performed better than those who did not. Examining the development level of reasoning and inductive thinking of engineering students, Tóth et al. (2021) point to differences between students and suggest the need to identify the thinking skills at the beginning of higher education by means of an input competence measurement.

In the education system of the Central European countries, secondary grammar schools are educational institutions at the secondary school level, which are characterised by general preparation in each discipline. In grammar school education, there is no specific priority given to certain subjects, although there may be high schools where they start a special mathematics class or a humanities or natural sciences class. However, even in these cases, general theoretical education is the main characteristic, unlike vocational secondary schools, where practical training comes to the fore. Logic or logical thinking is closer to thinking on a theoretical level, which also characterises secondary grammar school education. The text of the test tasks also primarily required theoretical consideration, which can be used to justify the significantly better results of those who graduated from secondary grammar school.

Regardless of the text context, the students studying mathematics or informatics performed above average in all but one task. Here we can see the result of the fact that students majoring in mathematics or computer sciences have adequately mastered the concepts of propositional logic during their studies, and these concepts are regularly present in their studies; they are a permanent part of them. They not only understand logical connections but can apply them in various tasks. The test results showed that the students majoring in mathematics or informatics solved the chemistry, physics or biology tasks similarly, meaning that the task context was less confusing for them. These students know, understand and can apply the given logic scheme, so the task context is not decisive.

On the contrary, we see the situation with students majoring in humanities and paedagogy. They probably already lack logical knowledge; they do not understand logical operations. In their case, this determines the low effectiveness of the tasks. Although a student majoring in humanities (e.g., history or philologist) is also expected to formulate his thoughts logically, the greater problem is evident in the case of students majoring in paedagogy. As future teachers, they will have to introduce their students to the methods of logical thinking and lay the foundations of scientific thinking.

We think that our research has several strengths but also limitations. Our research is specific in examining the elements of propositional logic and comparing its application to university students in different disciplines in the Hungarian speaking environment of the Central European region. During the mapping of the literature on the subject of research, we realised that it is difficult to find studies on propositional logic reasoning comparing results by scientific disciplines that are comparable to our topic, not only at the Central European level, but also at the global level. From this point of view, we consider our study to be a niche.

The strength of our research is also the sample size; however, the sample is not representative, 1,505 students from 15 universities participated in the research. Due to voluntary participation we had no influence on the sample composition, our sample was not balanced regarding gender or other background variables. As the countries of the participating university students have partially different education systems, this factor also affects the outcomes when comparing the students' performance by discipline. Another limitation is that the research tool was a non-standardised knowledge test, but it was previously pilot-tested.

## 6. Conclusion

The habits and form of thought gained in applying logic might have their place as a tool suitable for conceptual understanding in all disciplines. In logic, we learn how to use theories, deducing things from them, and we learn how to examine a theory from the outside, referring to the theories, analysing and finding ways it could be interpreted as true, or interpreted as false, and testing different models of the theory. This is a fundamentally important skill which is not straightforward to learn.

Our research focussed on examining university students' propositional logic thinking and knowledge of selected elements of propositional logic, considering their different fields of study. Based on the scores achieved, university students have significant differences in solving the tasks regarding the scientific disciplines by the student's study programme. The best results were achieved by students majoring in mathematics or computer science, while the worst results were achieved by students studying humanities. We found a significant difference in test results according to gender, age group, the student's type of secondary school leaving exam and also according to the parent's education level.

We conclude that those who know and understand mathematics (precisely, logic) have less problem solving a task that requires mathematical abstraction, but the task itself is in an arbitrary context. If this is true, it is also crucial for a good chemist, biologist or physicist to know and understand the relevant mathematical concepts. However, a good mathematician does not need to understand the specialised text and can still solve the task (of course, here we are thinking of tasks based on some mathematical abstraction). It follows that the university education of STEM specialists cannot be without the necessary mathematical foundations.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work, and approved it for publication.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1247653/full#supplementary-material

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# Basic logical operation skills and logical reasoning competences of university students in a Western region of Romania

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Empirical research results show that the system of logical operations and conclusion schemes does not become complete even in adulthood. Although we know other logical models besides the classical two-valued logical reasoning model, in higher education for students it is essential to know and apply the rules of the classical reasoning model. Proofs, reasoning and refutation are necessary in the case of several subjects, as scientific language uses many of logical operations. Our 2022 end-of-year research measured general logical basic-knowledge and operations in everyday life, mathematical, physical, chemical and biological contexts based on 246 university students' online testing. The students completed the tasks which required the correct conclusion in the highest proportion (69.02%), followed by the interpretation of 'at most'/'at least' (63.41%), and at least the negation (the negation of the 'at least', of 'exists' and of 'for all') (29.91%). Our results show that the correct interpretation did not become dominant in the case of all logical operations for these students. The everyday life problems were solved correctly by the highest percentage of students (70.05%), followed by problems in biological, physical and mathematical context. They were least successful (28.04%) in solving logical problems related to chemistry. This shows that our data cannot be analyzed without semantic content. Based on different statistical tests, we did not find a significant difference in performance between genders, but according to the human capital theory students of more highly educated mothers performed significantly better.

KEYWORDS

**basic mathematical knowledge, logical operations, higher education, problem solving abilities, academic enculturation content**

## 1. Introduction

Universities are places of acquaintance with reality through the eyes of sciences, where students are immersed in the 'intellectual life' of those around them; they gain social experience through the mediation of more competent peers (Ilyash, 2008). If learning is seen as enculturation in all its forms, involvement in the culture of a community, whereby one acquires and takes possession of the culture, the set of habits, skills, methods and tools of a group, community or society (Lave and Wenger, 1991; Lave, 1997; Allal, 2001), then university life is an entry into the scientific community, into the world of science. This is what Prior and Bilbro (2012) called academic enculturation. Prior and Bilbro (2012) identifies three research directions in the study of the content of academic enculturation. Our research is most closely related to linguistic-rhetorical studies, by investigating logical thinking among university students through different logical tasks. These tasks required the ability to recognise and understand the most commonly used logical syntaxes and operations, to understand the most relevant information, scientific context of the tasks.

In today's knowledge-based society, the role of research and science has increased, so developing higher-order thinking skills of higher education students is a priority. In a broadened concept of scientific thinking critical thinking and understanding, epistemic understanding, research skills, evidence-based reasoning skills and contextual understanding are essential for students (Murtonen and Balloo, 2019). Students need to be able to select relevant information, make research-based decisions, understand the process of knowledge construction, assess the validity of information sources, and apply reasoning skills, i.e., critical thinking skills (Seppälä et al., 2020). These higher-order thinking skills besides technical, social and behavioral skills are essential for the 21st century's citizens, because they are transferable across different subject areas and contextual situations, different jobs, occupations, and industries (Arum and Roksa, 2011; Avvisati et al., 2013; Shavelson et al., 2019). In recent decades more and more research has focused on the assessment and development of generic skills and competencies in higher education, such as critical thinking, problem-solving and complex reasoning (Shavelson, 2007; Nusche, 2008; Arum and Roksa, 2011; Tremblay et al., 2012; Zlatkin-Troitschanskaia et al., 2015; Shavelson et al., 2019; Braun et al., 2020; Tuononen et al., 2022). Basic logical operations are at the basis of these three internationally most studied generic skills.

Logical and critical thinking contribute to students' understanding of different disciplines (Durand-Guerrier, 2003; Cresswell and Speelman, 2020; Sobhanzadeh et al., 2021). Drawing on some other researches Adey and Shayer (1994) emphasise that formal reasoning is needed in higher education, because not only natural sciences, but social sciences also require deductive logical thinking, knowledge of the process of causal reasoning with its sub-processes as exclusion and control of variables, constructing and using formal models and logical reasoning. Many aspects of students' intellectual abilities are stimulated and developed during the school years, and the overall development of thinking, the correct use of logical operations is an important objective in mathematics education (Cresswell and Speelman, 2020). Basic logical operations allow us to carry out mathematical proofs and then draw further conclusions from them.

Formal logic and basic logical operations are important in mathematics and science, while in everyday life discussions we use informal logic. Before learning formal logic, we use informal logic of the language. „Conventions and norms of mathematical logic are clearly not inherent in everyday rationality or non-mathematical language" (Durand-Guerrier and Dawkins, 2020, p. 482). To be able to operate the norms and rules of formal logic in different contexts, it is primarily required to recognize the linguistic register in which we have to think, because the semantic content, the mental representations evoked by the context, determine how we think about the given topic, how we interpret logical operations: according to the rules of everyday language or according to the rules of formal logic (Dawkins and Cook, 2017).

## 1.1. Our research

There are very few studies on measuring student performance in higher education in Romania. To fill this gap, we examined a very small slice of the content of academic enculturation in order to get an idea about students' competences in basic logical operation skills and logical reasoning. Our research goal was to clarify what types of logical operations and tasks cause difficulties in interpretation and solving, and how much the context of the sciences influences the understanding and correct solution of problems. One of our research questions was whether the proportion of correct answers in different logical operation tasks depends on the scientific context in which the task is formulated or not. However, we also wanted to find out how the participants' gender, age, their parents' educational level, and involvement in teacher training influenced the success in problem-solving.

The Western Romanian region concerned is one of the ethnically and religiously most diverse peripheral regions of the country. Traditional values are highly valued in the region, the population is strongly bound to the area and the local community. Higher education institutions here are struggling to cope with the study-driven migration of youth to big cities' elite universities and abroad, it is difficult to recruit strongly selected students here, so regional recruitment is typical. The emergence and growth of non-traditional student groups, coming from families with limited financial resources, lower social classes, and different cultural backgrounds have given rise to the so-called „third mission of higher education": the wish to promote the cohesion of the diverse regional society (Kozma, 2010; Kozma and Ceglédi, 2010; Nyüsti and Ceglédi, 2012; Pusztai et al., 2012).

We conducted a conceptual replication study using the survey developed by Szarka et al. (2022), partially replicating their research and raising new questions. Also Slovakia and Romania are two Central and Eastern European countries, with very similar historical, cultural, and geo-political characteristics due to the 'nationalization' of teacher training (Kowalczuk-Walędziak, et al., 2023) there are main differences not only in teacher education policies, but in the whole educational process. Both in the initial and the replication study we found peripheral regions, with young universities which emerged around the turn of the millennium as a result of the educational policy conditions of the post-communist period and the subsequent changes in the European higher education area (Kozma, 2010, 2022). These changes have led to the development of a similar student base in both regions, which makes them comparable. We have formulated two hypotheses to test the results of the preliminary research (Szarka et al., 2022) regarding students' performance in logical tasks embedded in different scientific contexts on a different population, within a different educational space.

> *H1*: Students' gender does not influence on the performance of the logical thinking tasks.
>
> *H2*: Students' age influences on the performance of the logical thinking tasks: older students perform better, than younger.

In searching for alternative explanations of the original studies' results, two other hypotheses were formulated based on further literature review, as follows:

> *H3*: It is assumed that the educational level of the students' parents has an influence on students' achievements in logical thinking tasks. Students of parents with higher educational levels perform better than students of parents with lower educational levels.
>
> *H4*: Both the type of the logical task and the context of the task influence the effectiveness of the task solution.

## 2. Methods

Our study can be identified as a conceptual replication study, whereas by design it replicates most of the methodological features of the original study (Aguilar, 2020; Star, 2021; Perry et al., 2022). To test whether the results hold beyond the boundaries of the original study, we used a so-called scaling out model of exploration (Aguilar, 2020), using a study population with different geographical and educational characteristics than the original study.

We used the same research design and in most of the cases we followed the same statistical processing strategy as the original study to ensure comparability of the data. However there were some aspects of the original study's methodology we changed or added. To understand deeply the relationships between performance and the differences between logical tasks, we examined whether the type of logical operations or the context of the tasks were the determinants of performance. Compared to the original study we examined the effect of parental education on student performance as an independent variable.

### 2.1. Participants

The data were collected online in November and December 2022. The population consisted of undergraduate and master's students belonging to the Hungarian national minority of two universities from the Western Region of Romania: the Partium Christian University (PCU) in Oradea and Babeș–Bolyai University (BBU), the Satu-Mare extension. Random sampling was used; students completed the questionnaire online in the presence of a university lecturer.

The survey was completed by 246 students: 196 (79.7%) participants were from PCU, while 50 (20.30%) participants were from BBU. 72.76% of the participants were undergraduate students, and 27.23% were master's students. Distribution of students according to gender: 187 female (76.01%) and 59 male (23.98%). Distribution according to age: 217 participants aged 18–25 (88.21%), and 29 participants (11.79%) older than 25 years. The majority of respondents (over 95%) study other disciplines than STEM: economics, social sciences, humanities, languages or arts, and preschool and primary school teacher training. The percentages reflect the range of subjects offered by the two institutions.

### 2.2. Instrument

As a research tool, we used an online questionnaire developed during the COVID by a research group in Slovakia (Szarka et al., 2021, 2022). The questionnaire is divided into three parts: sociodemographic questions, different tasks for selected elements of propositional logic embedded in everyday life and four academic disciplines (STEM) contexts, and a rating of the tasks on a 5-point Likert scale. The variables related to the social background and demographic characteristics of the respondents (gender, age, parents' highest level of education, and characteristics of the study programmes) were identified as independent variables in the survey. The dependent variables were the results obtained in solving the tasks requiring logical thinking, basic logical operations and basic mathematical knowledge. The test compilers (Szarka et al., 2021, 2022) used three different types of logical operations: set A: understanding some quantifiers as 'at most/at least'; Set B: the negation of 'at least', 'there is', 'all', and finally Set C: reasoning: 'if … then', 'therefore'. All three problem sets contained problems of the same type, but were presented in different contexts. The basic general logical reasoning skills and operations were tested in the context of everyday life, mathematics, physics, chemistry, and biology. Except for one biological task, the tasks were multiple-choice questions with a single answer. The biological task was a short-answer task from set C, where students had to complete the sentence, to continue the reasoning. Each item was rated on a dichotomous scale (right/wrong). For each correct answer, 1 point was awarded. As examples we present in the Appendix three tasks from the three different types of logical operations, each in different contexts.

The third set of questions (assessing the difficulty of tasks) is not included in the present study.

### 2.3. Statistical analysis

The statistical analysis of the data was realized with Excel and R statistical software. The tasks measuring logical operations were of nearly the same difficulty. To verify the reliability of the test we used Kuder–Richardson formula 21 (KR-21), which is a special case of Cronbach's Alpha in which the items are binary variables, usually scored as 0 or 1, and the tasks are of nearly the same difficulty. Based on the KR-21 our test is reliable, our value is 0.7, and the results are consistent. In order to compare the standard deviation squares of different subsamples we used the *F*-test and Anova, and to compare the mean of subsamples, we used T-test for Two-Sample Assuming Equal Variance or *T*-test for Two-Sample Assuming Unequal Variance. Searching for significant correlations between parents' educational level and students' performance chi-square test was applied. In order to determine which variables determine the results more significantly (type of logical task or context), multiple linear regression analysis was used.

## 3. Results

From a maximum of 15 good answers the average test score for $N = 246$ participants was 8.12 (SD = 2.18). The median value was 8. The participants resolved correctly at least 3 tasks, and they resolve up to 14 tasks correctly. 54.12% of questions were correctly answered.

## 3.1. Overall results based on the type of the logical operations required in the tasks and their context

Our results show that the difficulty of the task types, therefore the difficulty of basic logical operations differs as presented in Table 1. As every set of tasks is composed of 5 tasks of a kind, a maximum of 5 points could be achieved. In Set A tasks at least 1 task was correctly resolved by everybody (13 students get 1 point out of 5), but in Set B, and C we found participants, who could not resolve even one of five negation or reasoning tasks. In Set B 47 students achieved 0 points, which means 19.11% of students, in Set C just 1 student. Most of the perfect solutions were in set C, in the reasoning, and conclusion-making tasks: 48 students (19.51%) solved all 5 problems correctly.

The students completed correctly in the highest proportion the tasks set C which required reasoning (69.02%, 849 good answers), followed by the interpretation of 'at most', 'at least' (63.41%, 780 good answers), and at least the negation of 'at least', 'exists' and 'for all' (29.91%, 368 good answers). The Single-factor ANOVA shows that there is a significant difference in the success rate of solving different sets of tasks ($F = 228.83$, $p \leq 0.001$), and negation of different statements including quantifiers such as 'every/everyone', 'at least', 'there are' is the most difficult logical operation for students. The most difficult task was to negate the sentence with 'at least'. Although, according to the rules of formal logic, a relatively simple situation from everyday life had to be negated ('I have been to Prague at least 6 times'), from 246 participants a total of 36 correct answers were received, giving a 14.63% success rate. The same low percentage of students (19.92%) negated correctly a sentence in chemistry context: '2 of the elements in the periodic table are in the liquid state'.

Grouping the tasks by their context, we see that context plays a significant role in the interpretation of propositional logical operations. Table 1 presents the descriptive statistics of the tasks grouped by context. In everyday life context at least 1 task was correctly resolved by everybody (7 students get 1 point of 3), but in scientific contexts we found participants, who cannot resolve even one of three tasks. In the chemistry context 102 students achieved 0 points, which means 41.46% of students. Most of the perfect solutions were in the biology context: 62 students (25.20%) solved all 3 problems correctly.

The tasks related to everyday life were solved correctly by the highest percentage of students (70.05%), followed by problems in biological (65.85%), physical (56.78%) and mathematical (49.86%) contexts. The tasks embedded in a chemistry context were the weakest performed (28.04%) by the students. The Single-factor ANOVA shows that there is a significant difference in solving problems related to the context ($F = 97.31$; $p \leq 0.001$). There were two tasks related to everyday life that were solved correctly by more than 95% of the participants.

Looking at the overall score achieved by the students, it can be seen that it depends both on the type of logical operation used in the task and the context of the task. Using multiple linear regression and examining all the factors simultaneously, we find that the context of the tasks has a significant effect on the student's performance, while there is no significance for the logical operation used (R-square value is 1, $p = 0.00$). From this we conclude that context has a greater effect on task performance than logical operation.

## 3.2. Results presented by gender and age

The sample is unbalanced in terms of gender due to the high proportion of students enrolled in preschool and primary school teacher training (See Table 2). To assess the differences between the results obtained in solving the tasks, an $F$-test and, a $T$-test were used, but there were no significant differences between males' and females' test scores, not even in one specific type of task or context.

The sample is unbalanced in terms of age, but represents the population of the examined Western-Romanian universities. As above an $F$-test and, a $T$-test was used to explore the differences between the specified age-groups. Table 2 shows the main descriptive statistics regarding the age-group's achievement, and specifies two task types where there are significant differences. The understanding and usage of quantifiers tasks, were significantly better performed by younger students: the average of correct answers was 3.24 for younger students, and 2.68 for older students ($t = 2.79$, $p \leq 0.01$). Although older students performed better in the other two types of logical operations, there are no significant differences. On the other hand, when the tasks were grouped by context, the older students performed significantly better on the tasks embedded in a chemistry context, which caused the most

TABLE 1 Descriptive statistics of task sets and contexts ($N = 246$).

| | Type of tasks | | | Contexts of tasks | | | | |
|---|---|---|---|---|---|---|---|---|
| | Set A (A1, A2, A3, A4, A5) | Set B (B1, B2, B3, B4, B5) | Set C (C1, C2, C3, C4, C5) | Everyday life (A1, B2, C4) | Mathematics (A3, B5, C2) | Physics (A2, B3, C3) | Chemistry (A4, B4, C1) | Biology (A5, B1, C5) |
| Mean | 3.17 | 1.50 | 3.45 | 2.10 | 1.50 | 1.70 | 0.84 | 1.98 |
| Mode | 3 | 1 | 4 | 2 | 1 | 2 | 0 | 2 |
| Standard Deviation | 1.00 | 1.13 | 1.15 | 0.39 | 0.92 | 0.91 | 0.85 | 0.77 |
| Minimum | 1 | 0 | 0 | 1 | 0 | 0 | 0 | 0 |
| Maximum | 5 | 5 | 5 | 3 | 3 | 3 | 3 | 3 |
| Success rate | 63.41% | 29.91% | 69.02% | 70.05% | 49.86% | 56.78% | 28.05% | 65.85% |

TABLE 2 Average test scores by gender and age.

| | Type of tasks | | | Context of tasks | | | | | Total score |
|---|---|---|---|---|---|---|---|---|---|
| | Set A | Set B | Set C | Everyday life | Mathema-tics | Physics | Chemistry | Biology | |
| Meal ($N=59$) | 3.05 | 1.59 | 3.32 | 2.08 | 1.58 | 1.66 | 0.71 | 1.93 | 7.97 |
| Female ($N=187$) | 3.21 | 1.47 | 3.49 | 2.11 | 1.47 | 1.72 | 0.88 | 1.99 | 8.17 |
| *t* | *−1.05* | *0.64* | *−0.90* | *−0.38* | *0.77* | *−0.38* | *−1.35* | *−0.46* | *−0.55* |
| *p* | *0.29* | *0.52* | *0.37* | *0.70* | *0.44* | *0.71* | *0.18* | *0.65* | *0.59* |
| Between 18–25 year ($N=217$) | 3.24 | 1.47 | 3.43 | 2.10 | 1.51 | 1.73 | 0.79 | 2.01 | 8.13 |
| Older than 25 year ($N=29$) | 2.68 | 1.69 | 3.62 | 2.14 | 1.41 | 1.52 | 1.21 | 1.72 | 8.00 |
| *t* | *2.79* | *−0.99* | *−0.84* | *−0.54* | *0.51* | *1.00* | *−2.49* | *1.89* | *0.31* |
| *p* | *0.01* | *0.33* | *0.40* | *0.59* | *0.61* | *0.32* | *0.01* | *0.06* | *0.76* |

problems for the participants. Older students' performance was 1.21, younger students' 0.79 ($t=-2.49$, $p \leq 0.02$).

### 3.3. Results presented by parents' highest educational level

As an explanatory variable we used parents' highest educational level. No significant correlations were found between parents' highest educational attainment and students' test scores for the three types of operational logic tasks tested. Concerning the contexts of the tasks, fathers' educational level had no significant impact on students' performance, but mothers' educational level had. As Table 3 shows, students of mothers with tertiary education perform better than students of mothers with lower educational levels in all contexts. The largest difference is seen in the proportion of correct answers to the tasks embedded in the physical context: while students of mothers with tertiary education answered the questions correctly in 64.81% of cases, participants of parents with lower educational level answered correctly in 56.86% at most.

Grouping participants' correct responses by their mothers' highest educational level, using a chi-square test ($\chi^2=61.67$, $p \leq 0.001$), we found a significant correlation between mothers' higher education and better students' performance in different contexts.

## 4. Discussion

The significance of the present study lies in the skill assessment methodology. There is a lack of literature on the basic logical operation skills of university students, although these operations are essential for critical thinking and scientific thinking in higher education. With our conceptual replication study, we focused on the comprehension of the relationship between logical operations and context, and the conditions that led us to the presented results. Except for a few minor differences, our results confirm the lessons from the Slovak studies by Szarka et al. (2021, 2022). Based on our new sample of research from another country, we can generalise the following findings: both the types of logical operations and the contexts of the tasks determine students' performance. We can also establish the same order of difficulty in both countries based on the type of logical operations (reasoning, understanding quantifiers, negation of quantifiers) and based on the context of the tasks (everyday life, biology, physics, mathematics, chemistry). This suggests that both the type of logical operations and the context are determined by some immanent characteristics rather than by the educational systems. Regarding the examined logical operations some researchers find that understanding quantifiers and mainly negation of quantifiers is one of the most problematic tasks (Dubinsky and Yiparaki, 2000; Ferrari, 2004; Ye and Czarnocha, 2012; Bardelle, 2013; Hazem, 2017). This is because some quantifiers have to be reformulated in a more formal language for comprehension, and students rarely encounter formal language before higher education (Mesnil, 2017), they are not familiarized with formalisations and visualizations to support logical tasks (Bronkhorst et al., 2022). Students' difficulties with the measured logical operations, and comprehension of concepts "can be related to their epistemological complexity or to their use in the classroom" (Mesnil, 2017, p. 217), to the lack of awareness of the importance of the mathematical language used in such tasks (Bardelle, 2013). Ferrari's (2004) and Bardelle's (2013) experiments prove that there is a typical mistake to ignore the differences between everyday registers and mathematical ones because of the overlapping and interference between some technical terms from mathematical language and everyday language.

One of the limitations of the study is the relatively small sample of students from universities in the peripheral border region, so the results are not representative of the whole country. Compared to the performance of students in Slovakia (Szarka et al., 2021, 2022), our students' poor results are in line with the results of the PISA surveys, where Romania's scores are well below the OECD average in all areas year after year (Lazar, 2021; Mirea et al., 2021; European Union, 2022), while Slovakia is much closer to the OECD average. The overall

TABLE 3 Distribution of correct answers by mothers' educational level and percentage of correct answers from possible answers.

| Mothers' educational level | Everyday life | Mathematics | Physics | Chemistry | Biology | Total |
|---|---|---|---|---|---|---|
| Lower secondary education | | | | | | |
| *Success rate* | 105 | 74 | 78 | 39 | 94 | 390 |
| (*N* = 50) | *70%* | *49.33%* | *52%* | *26%* | *62.67%* | *52%* |
| Upper secondary education, without baccalaureate | | | | | | |
| *Success rate* | 157 | 106 | 126 | 67 | 142 | 598 |
| (*N* = 74) | *70.72%* | *47.74%* | *56.76%* | *30.18%* | *63.96%* | *53.87%* |
| Upper secondary education with baccalaureate | | | | | | |
| *Success rate* | 178 | 131 | 145 | 65 | 174 | 693 |
| (*N* = 85) | *69.80%* | *51.37%* | *56.86%* | *25.49%* | *68.24%* | *54.35%* |
| Terciary education | | | | | | |
| *Success rate* | 77 | 57 | 70 | 36 | 76 | 316 |
| (*N* = 36) | *71.30%* | *52.78%* | *64.81%* | *33.33%* | *70.37%* | *58.52%* |

development of logical thinking is an important objective in mathematics education all over the world. The mathematics curriculum is divided into different areas and topics, and almost all of them aim to develop logical thinking. The areas vary from country to country, while in the Slovak curriculum for mathematics logic, reasoning and proof are separate areas, in Romania there is no explicit inclusion of such topics in the curriculum, and elements of logic, the logic of judgement are embedded in other topics. Learning mathematics and logical thinking also depends on the pedagogical practices, the content, and the methodology used by the teachers. The differences between the teacher training systems of these countries are measurable in terms of time, curriculum, and pedagogical, psychological, and methodological knowledge (Bordás, 2015; Nagy, 2015; Luchenko and Yurchenko, 2023). In Romania, much more emphasis is placed on the scientific disciplinary training of teachers than on pedagogical-psychological subjects. These factors certainly combine to influence students' scores on logical tests.

Neither age nor gender has a significant effect on test scores. Our results support researches showing that there is no significant difference between boys' and girls' performance in mathematical and logical tasks (Cassar and Musumeci, 2017; Ramírez-Uclés and Ramírez-Uclés, 2020). According to human capital theory the parents' educational level, is one of the most important background factors in educational research on students in the peripheral area under study (Róbert, 2004; Pusztai, 2009, 2011; Ceglédi, 2015a,b,c, 2018; Pusztai and Ceglédi, 2015). Several studies have shown that the parents' educational level, including the mother, is closely related to academic performance, especially students' mathematics achievement (Davis-Kean, 2005; Kodippili, 2011; Crede et al., 2015; Dixson et al., 2018; Hidayatullah and Csíkos, 2023). Our study demonstrated a strong positive relationship between maternal education and students' basic logical operation skills.

The results show that the refutation or negation of quantitative determinants is one of the most difficult logical operations, regardless of the context of the task. The different results achieved in different contexts (difficulty in solving chemistry problems) indicate that students' thinking is context-dependent and that many of them are not able to handle abstract logical inferences independently of context. As the majority of our sample consists of students from preschool and primary school education programme, testing and developing their elementary reasoning skills is important not only for their academic enculturation but also for their future work. The results suggest that a subject should be introduced where these competencies in basic logical operation skills and logical reasoning can be practiced and developed. There is evidence that thinking skills (critical thinking, problem-solving) can be fostered in tertiary education (Saavedra and Saavedra, 2011) in theory-intensive programmes (Avvisati et al., 2013), using active and collaborative learning (Roksa and Arum, 2011), problem-based learning (Hoidn and Kärkkäinen, 2014).

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Author contributions

ED: Data curation, Methodology, Writing – original draft. AB: Conceptualization, Investigation, Visualization, Writing – original draft.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2023.1273602/full#supplementary-material

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# Bringing engineering into primary science classrooms using engineering design and community of practice approach—An evaluation of STEM × Play program

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Due to the rapid growth of STEM-skilled jobs, there is an urge of introducing engineering in earlier years of schooling to not only flourish students' motivation and interest but to also acquire the required skills for surviving in the high digital demand environment. This paper aims to share an innovative pedagogy–STEM × Play in-curriculum program and to report the post-program evaluation of primary school students' perceptions about and attitudes toward learning STEM and teachers' perception of teaching STEM. There was evidence of positive student learning outcomes including critical skills needed for STEM professions such as comfort with failure, collaboration, critical thinking and problem solving. Mentors from universities and industries were found crucial for improving teachers' STEM skills.

KEYWORDS

**STEM, engineering design approach, community of practice, theory of change, STEM × Play**

## 1 Introduction

As reported in Burnett et al. (2019), the existing engineering education system is not coping with the rapid pace of change in digital structures and systems. To meet the future expectations and global workforce demand for economic challenges, urgent action in the reform of engineering education systems is required to develop proficiencies in Science, Technology, Engineering and Mathematics (STEM) education. Education policymakers, STEM educators, engineering and related industries are stressing the urgency for improving students' STEM knowledge and uptake of STEM careers (Marginson et al., 2013). However, results of studies (e.g., McDonald, 2016) have revealed that students' decreasing interests in STEM subjects are "attributed to transmissive, teacher-centered pedagogies; perceived irrelevancy of school science to the real world; heavy, difficult and content-driven curriculum . . ." (p. 536). Among different impacting factors, teaching pedagogy bears the most significant influence on students' motivation and interest in studying mathematics and science in school (Krapp and Prenzel, 2011). Thus, researchers (e.g., English and King, 2015; McDonald, 2016) have called for efforts that promote engineering-based problem solving, inquiry-based pedagogical practices as well as integration of technology and engineering in earlier years of schooling due to the decline of students' interest in science and mathematics at an early age.

However, the low visibility of engineering in K-12 education has adversely impacted students' motivation in studying STEM subjects (Corrigan and Aikens, 2020). Findings of English's (2015) study indicated that early learning experiences in engineering and technology could enhance students' higher order thinking, problem solving skills and academic achievement. Thus, early incorporation of engineering experiences into the classroom can extend students' appreciation and awareness of STEM subjects (English et al., 2013) and better facilitate students to pursue STEM and related subjects in high school. Subsequently, the demand of teaching engineering knowledge as early as from primary schools was emerged.

This paper aims to share an innovative pedagogy that brings engineering into primary science classrooms using engineering design and community of practice approach and to report the evaluation of primary school students' perceptions about and attitudes toward learning STEM and teachers' perception of teaching STEM after engaging into an in-curriculum engineering design process for solving real world problems of local relevance.

## 2 Literature review

### 2.1 In-curriculum program pedagogy—Engineering design process

In the past decade, STEM education has been overlooked the potential role of engineering and technology in enabling students to engage in authentic and meaningful scientific activities that are connected to the increasingly digital world (Bybee, 2010). Researchers such as Frykholm and Glasson (2005) identified engineering as a key to locating the entry points for STEM subject integration. Though there is no agreed curriculum for how engineering could be introduced in schools, a common teaching objective under discussion is around teaching broad concepts of the engineering design process through solving real-world challenges (such as Barak, 2013). The engineering design process (also known as the engineering method) is a systematic approach to design and problem-solving that is taught at university-level engineering degree courses and practiced in engineering industry (Atman et al., 2007). Whilst the specific steps of the engineering design process varies slightly amongst engineering education literature (e.g., Dym and Little, 2009), generally, the (iterative) process of engineering design is comprised of the following key stages: (1) Identify and explore the problem, needs and constraints; (2) Explore available solutions to the problem (conceptual design); (3) Evaluate alternative solutions to meet design requirements; (4) Decide on preferred solution; and (5) Detailed design, prototyping, testing and refining the solution.

Pedagogically, a new emphasis of "practice turn" which highlights learning by doing and practising has been put forward in pedagogical shift: a shift from simply teaching the scientific and mathematics content to creating an epistemic culture in where students actively work in authentic scientific inquiry processes (Forman, 2018). Barak (2013) suggested that teaching the engineering design process could serve as an important ingredient in putting STEM into practice. Engaging students in engineering design process is to nurture their engineering thinking and engineering habits of mind (National Research Council [NRI], 2012); they are all about developing students' higher-order capabilities such as systems thinking, problem solving, creativity and collaboration in an interdisciplinary scientific-engineering-technological context (Barak, 2013). More importantly, the unique features of engineering design process–modeling and feasibility analysis–enable students to thoroughly evaluate the viability of each idea when choosing the optimal solution so that their sophisticated thinking can be cultivated (Lin et al., 2021).

Kelley et al. (2020) point out that the engineering design process serves as a platform for situated learning because the problem context is not only authentic but also bounded by science and engineering practices. Engineering creates opportunities to learn as well as apply science knowledge, mathematics knowledge and reasoning during the design process (Lin et al., 2021). Furthermore, when students situate the problem they choose from their local environment and community, they are likely to highly engage in this activity and their learning would be grounded within this context, which makes engineering as well as the other components of STEM appear to be relevant to their life. In this way, the engineering design process can be considered as an entry point for STEM integration.

### 2.2 Community of practice

Bringing engineering into classroom practice requires strong conceptual knowledge of how to integrate and apply STEM content as well as how students learn (Kelley and Knowles, 2016). Nesmith and Cooper (2021) acknowledged that school children were able to engage in engineering and science investigation when they were facilitated by skilled and knowledgeable teachers. Yet, one of the many but critical factors that obstruct school students being exposed to engineering is that most of the STEM teachers are not trained to integrate STEM into their existing school curriculum (Kelley et al., 2020). Furthermore, many teachers are lacking authentic scientific research and engineering practice because they have never practised as an industry professional or left industry some time ago. Their limited cognitive structure of engineering design thinking hampered their ability to teach STEM (Lin et al., 2021). Therefore, using a community of practice approach alongside the engineering design process to bring in engineering experts to assist teachers' teaching and students' learning may be beneficial.

A community of practice is defined as "groups of people who share a concern, a set of problems, a passion about a topic and who deepen their knowledge and expertise in that area by interacting on an ongoing basis" (Wenger et al., 2002; p. 4). Viewing learning as a production of social structure is the fundamental concept of community of practice. The power of engaging a community of practice in the STEM classroom has been shown to be impactful. For instance, engaging local community experts as STEM partners such as engineering undergraduate students in STEM classrooms can narrow down the power distance; it creates a "safe" environment (free of academic judgment) for school children to develop authentic engineering practice through varieties of activities, problem solving, information seeking and sharing, building things, evaluating and refining outcomes (Kelley and Knowles, 2016). As the idea of a community of practice involves learning on the part of every participant, teachers' active collaboration with STEM partners has the potential to increase teachers' STEM knowledge and foster their understanding about real world engineering practice and scientific inquiry (Kelley et al., 2020).

## 3 Pedagogical framework

This innovative pedagogy "STEM × Play" program, bringing engineering into primary science classrooms and using engineering design as well as community of practice approach aims to improve primary students' attitudes toward learning STEM and teachers' perception of teaching STEM after engaging into an in-curriculum engineering design process for solving real-world problems. In 2019 the Women in Engineering and IT team at the University (authors' affiliation) introduced this primary school in-curriculum program. Mapped to the Science and Digital Technologies curriculum with indirect links to the Mathematics curriculum (in Australia), the program is a multi-touchpoint targeted at Year 5 and 6 students (aged 10–12).

This program uses engineering design process as pedagogical practice, bringing curriculum content to life and allowing students to work with engineering expertise from the university and industry on real-world problems that interest and are relevant to them. Students undertake engineering design thinking and "future of work" skill development, including computational thinking and collaboration with their peers. The impact on teaching and learning can be sustained post-program, as families are also engaged in the program and teacher professional development embedded to enable long-term capacity development.

### 3.1 Underlying principle of "STEM × Play"—Theory of change

The STEM × Play program employed a Theory of Change (Weiss, 1995) in its program design. Theory of Change defines long-term goals and then maps backward to identify necessary pre-conditions. It is a specific type of methodology for planning, participation, and evaluation to promote social change when different pre-conditions have been identified potentially responsible for promoting this change. Informed by the evaluation of previous (authors' affiliation) Women in Engineering and IT programs and existing literature as reviewed in the Australian Government's Women in STEM Decadal Plan (Australian Academy of Science, 2018), hands-on learning experiences, building teacher capacity, real world application, multiple meaningful engagements, engaging with families and a community of practice, and early exposure to STEM have been recognized as the necessary pre-conditions for improving primary students' confidence, awareness of opportunities, identity with STEM and interest in STEM play. The diagrammatic Theory of Change for this study is presented in **Figure 1**.

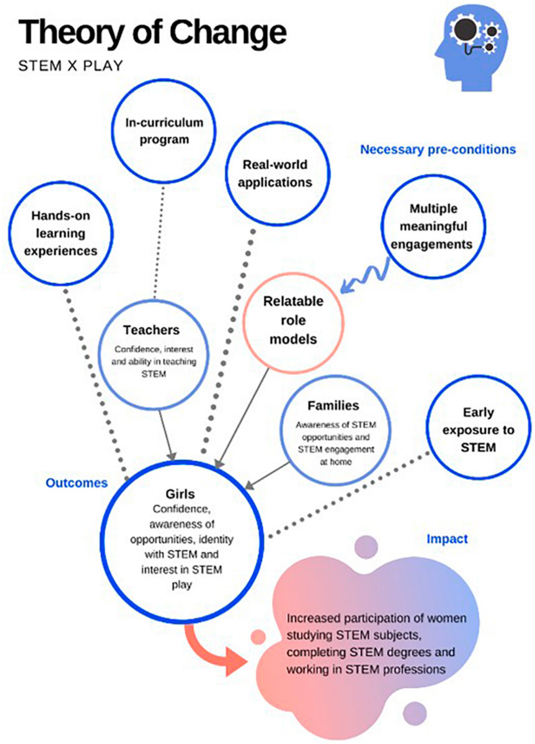


FIGURE 1
Theory of change for STEM × Play program.

### 3.2 The STEM × Play program structure

The program was structured on project-based learning applying the engineering design process, with curriculum content was embedded in activities to enable students' skill development. Each lesson was 1.5–2 h long to fit in with school class times and took place during the same time each week for 8 weeks.

The design problem statement (also known as the driving questions) for the projects were aligned with the Science curriculum content to ensure that the problems students chose would be related to their current term's unit of work. Students also had to use engineering and/or information technologies in their design solution and prototype. **Figure 2** presents the overall flow of the engineering design process for 8 weeks. The weekly Science curriculum content and related activities are elaborated below and presented in **Figure 3**. Examples of student projects are illustrated in **Figure 4**.

#### 3.2.1 Empathy mapping

In week 1, students were asked to think about the issues different people may encounter as relevant to the Science unit of work. Students then drew empathy maps for a chosen stakeholder and writing down all the things that people might think, feel, see, hear, do and say.

#### 3.2.2 Defining the problem

In week 2, students investigated and identified the problem. Defining the problem requires critical thinking about the root cause of the problem. Students started brainstorming all the problems,

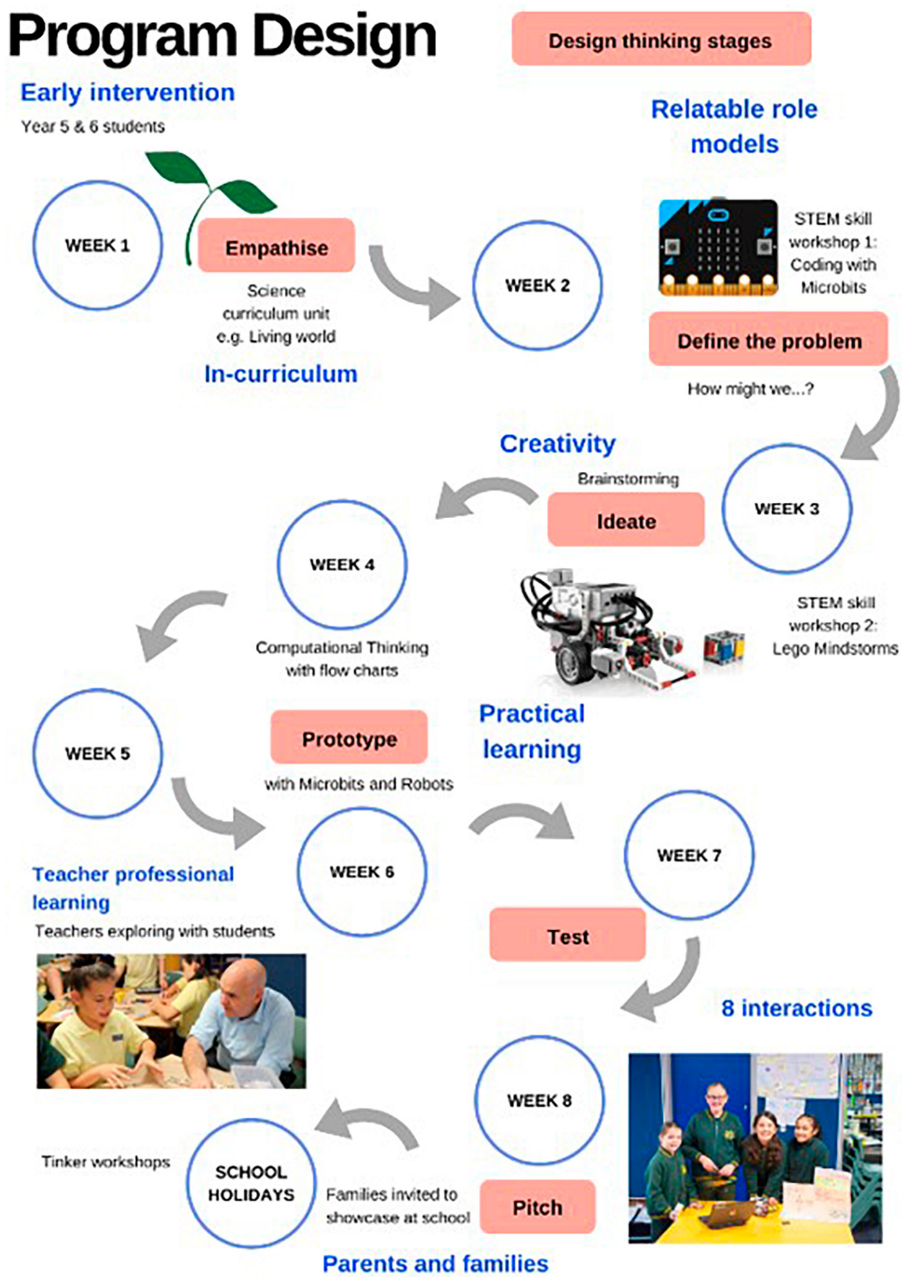


FIGURE 2
The engineering design process and weekly activity in STEM × Play.

then grouped similar ones and chose one cluster to focus on. The output of this lesson was to have a single problem statement which started with, "How might we use technology to. . ..?" The hands-on learning with various technologies began from the week 2 lesson to give students time to get comfortable with the technology before prototyping their own solutions to their design problem.

### 3.2.3 Ideation

In week 3, the students brainstormed solutions to their design problem using "How might we use the Microbit to . . .." The aim of the lessons was also to teach/reiterate fundamental computational thinking concepts including variables, inputs, outputs, loops and conditional statements which would allow students to create their own algorithms and logic for their design problem such as making a soil moisture sensor for farmers or a musical instrument that measured the conductivity of different materials.

### 3.2.4 Refine the solution

In week 4, students then developed an evaluation criteria or an "ideas checklist" to critically think about their design ideas. This helped them to decide on the solution to prototype.

### 3.2.5 Prototyping, testing, and troubleshooting

In weeks 5 to 7, once students had decided on a solution, they developed a flowchart with the logic of their idea. The flowcharts were particularly useful for facilitators, mentors and teachers to talk

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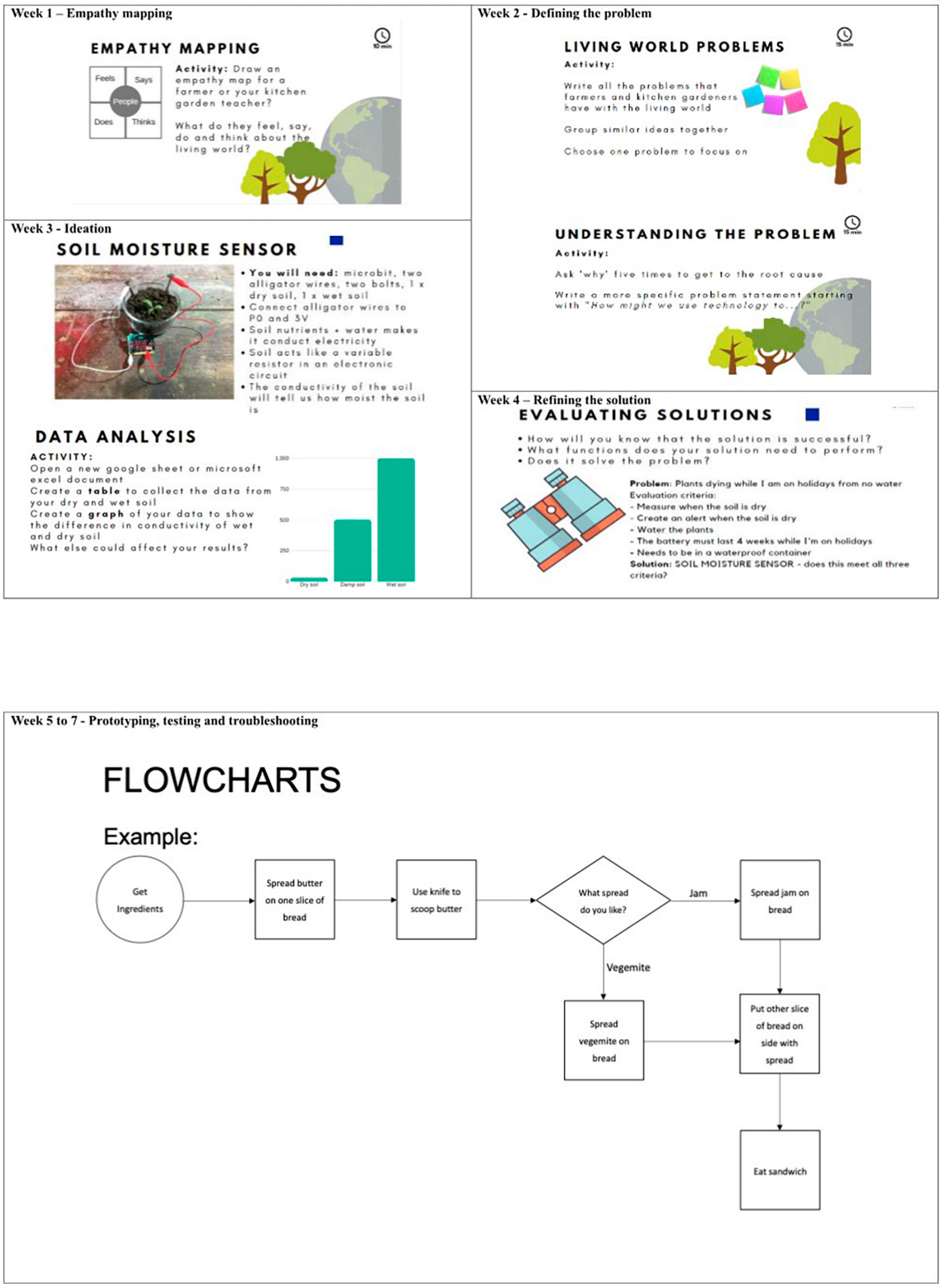


FIGURE 3
The weekly science curriculum content and related activities for week 1 to week 7.

through the students' ideas. Students needed to go through several iterations of their idea, in some cases returning to the ideation phase of the engineering design process.

### 3.2.6 Pitch ideas

In week 8, families, teachers and students from other grades and the school Principals were invited to the project showcase. Students set up their prototypes, similar to a Science Fair, along with all the artifacts from the engineering design process.

## 4 Participants

### 4.1 School and students

Schools selected were based on existing relationships and teacher willingness to implement the program. Five schools including 4 co-educational government schools and 1 Catholic single-sex school participated in this program. Across the five schools, 448 students (224 boys and 224 girls) from Years 5 and 6 aged 10–12 participated. Their families were well-informed of the

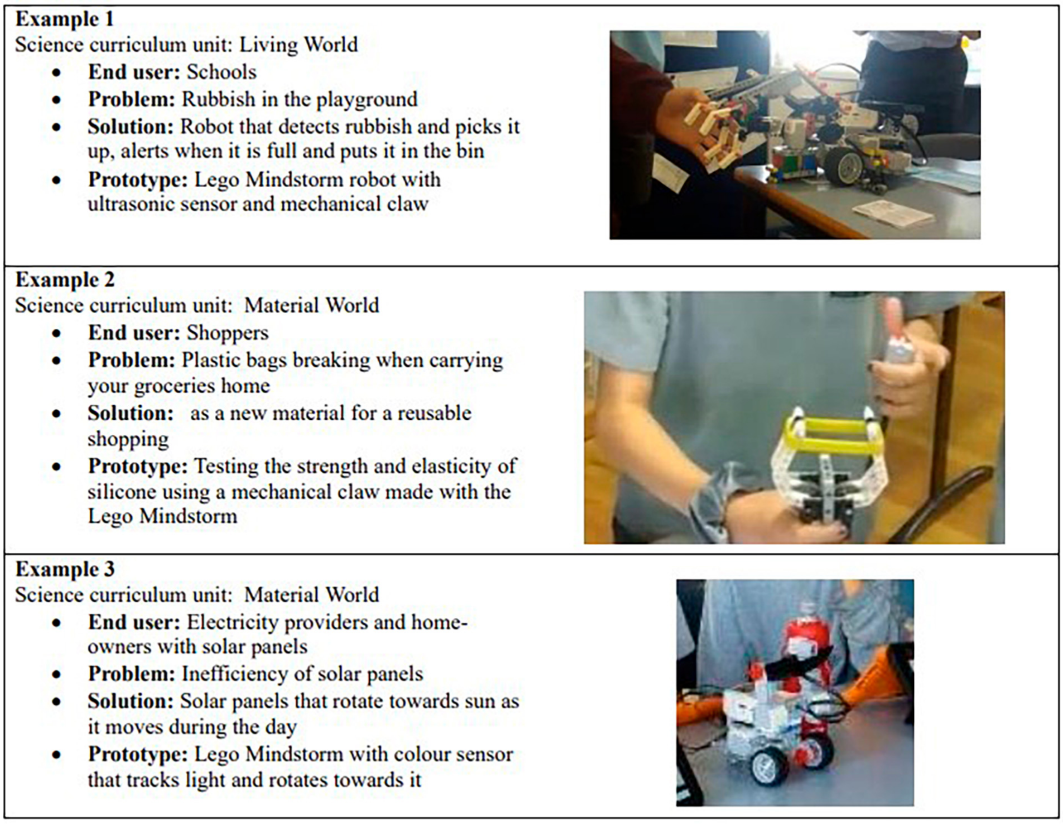


FIGURE 4
Examples of student project.

program, invited to the project showcase and into the classroom to learn alongside students during class-time. Eighteen teachers participated and all 5 principals gave their support to take part. In some schools, teachers from other grades participated in lessons for their own professional development.

## 4.2 Teachers and their roles

There were 18 participating teachers who played the roles as "observer as participant" and assisted in delivery of Science Curriculum content, which gave context for students to define their problems. They co-facilitated the program activities particularly in regard to student behavior, engagement and effective communication techniques, and prepared for the classroom and equipment for students' design prototyping. This co-facilitation also served as informal professional development, especially in the use of STEM technologies. The teachers also assisted in allocating class time for students to work on their projects prior to the final program showcase, and some administrative tasks such as collection of consent forms.

## 4.3 Families

All the families of the participating students were provided with a resource pack to start conversations about STEM at home, increase their understanding of the range of opportunities available, and information about the program, including questions to ask their children at home about their design process and project to continue the learning outside of the classroom. They were invited to join students in the classroom during project lessons and to participate in the final program showcase as an audience.

## 4.4 Mentors (i.e., community of practice)

The program in-classroom delivery was facilitated by 52 mentors. Among the 52 mentors, 27 were undergraduate students (of University–authors' affiliation) who were selected based on their STEM background, ability to explain concepts to primary school students, and ability to commit to 8 weeks of lessons. Twenty-five mentors were from the University and industry partners and were selected based on relationships with (University–authors' affiliation) Women in Engineering and IT, and their tertiary education area of study or professional background. The key role of mentors was to guide the students through their projects to develop their STEM knowledge in general and engineering design knowledge in particular as well as problem-solving skills. They also introduced different devices and resources (such as Microbits, Lego, ThinkerCAD and Draw.io) to the teachers and provided them support.

# 5 Program evaluation process

## 5.1 Participants

As confined by the research ethics, we were only allowed to collect data from the students, teachers and parents for this program evaluation.

### 5.1.1 Students

To understand the STEM perception and attitude changes of the students after engaging into an engineering design process, all the participating students were invited to complete a pre- and post-program survey. However, due to some school administrative issues, the survey response rate was less than 10%. Thus, in each school 6–7 students, who were randomly chosen and gave consents to interview, were invited to participate in a post-program focus group interview conducted at their school. A total of 32 students (17 girls and 15 boys) responded to a thematic question "how your ideas of STEM changed (if any) as a result of the program?" in the interviews. In this program evaluation, only the interview data is reported.

### 5.1.2 Teachers

One teacher from each school was also interviewed individually after the program. Five teachers in total were free to express their ideas around the thematic questions: "what changes in students' STEM learning attitudes you could see," "what factors contributed (if any) to changing your perception of teaching STEM," and "what you would request to keep for the next program."

### 5.1.3 Families

A total of 30 parents from 5 schools completed a post-program survey online, including few open-ended questions such as "what changes (if any) in your kid's STEM learning attitudes you could see," and "what key components (if any) of the program contributed to these changes."

## 5.2 Data analysis

Qualitative data from the student interview, teacher interview and families' responses to the open-ended questions in the online survey were transcribed using a combination of online software and manual transcription. The data were coded to the concepts including "learning outcomes of using STEM equipment," "work collaboratively," "learning about failure," "perception of learning STEM," "perceptions of STEM as problem-solving," "mentor scheme," and "community of practice" in an attempt to evaluate the students' and teachers' changes in perceptions about and attitudes toward STEM learning and teaching. Ultimately, four significant themes regarding students' perception and attitude changes and one major factor contributing to changing teachers' perception of teaching STEM were identified (see the headings and sub-headings in "6. Results").

# 6 Results

The organization of reporting and discussion of the results is driven by the themes/factors, that were identified and appeared significantly in the interviews and post-program online survey.

## 6.1 Changes in students' perceptions about and attitudes toward STEM learning

Overall, four major themes of changes in students' perceptions and attitudes were identified from the post-program focus group student interviews, teacher interviews as well as the families' responses to the open-ended questions in the online survey. The students' (a) understanding of STEM and (b) their attitudes toward failure have been altered significantly. They no longer saw STEM just as sets of science, technology, engineering and mathematics knowledge sat individually in the curriculum but integrated tools for solving real-world problems. Failure no longer frightened them away from learning new and difficult concepts but rather, as part of the learning journey that would lead them to the right direction eventually. Building on the reduction of fear about failure, (c) the students' increasing engagement in STEM activities and (d) improvement in problem solving skills were also revealed.

### 6.1.1 Understanding of STEM: from students' interviews

First, the students were aware that they had a better understanding of the notion of STEM, which was not only concerned about the content knowledge of science and mathematics but "more about finding solutions to different things" (Student A). They admitted that they had no idea of what STEM was at the beginning of the program but when they proceeded into the school term, they started learning that "it's got stuff to do with problem solving" (Student B) and they "could make something that could actually work in the future" (Student C). They acknowledged that the program "made science more fun instead of just learning oxygen and stuff" (Student D). Some students even declared when they first started, they "thought it wasn't going to be that fun and we [they] would just learn about science like we [they] normally do but we [they] got to build things" (Student E). Other students "thought it [STEM] was all [about] science but they do stuff with technology as well" (Student F) and "it was not just about fixing computer but it's about actual coding" (Student G). Some students did not like coding at the beginning but when the program proceeded, they "actually like[d] it a lot" (Student H). More importantly, the students eventually learnt that the programming and building things in engineering were for "finding solutions and going through the process is [was] fun" (Student I). Student J concluded that "it [STEM] was certainly fun and I (she) guess it just sort of changed it in a good way, in terms of like, it's a bit more, fun."

### 6.1.2 No fear about failure: from teachers and parents' interviews

The changes in perceptions and attitudes reported in the previous section were from the students' self-reflections. However, there were some deep-down changes that the students did not realize but the teachers and families who know them well could identify. "No fear about failure" was one major attitude change that both the teachers and families could clearly observe after the program. The teachers acknowledged that their "students are [were] becoming increasingly accepting of failure and recognizing it as a step to success especially when coding" (Teacher A). They were also aware that their students have developed "confidence, improved collaboration, understanding that failure is [was] the way of learning and trying again" (Teacher B) had no harm. Other teachers even noticed their students had "more engagement with the equipment and greater risk taking in their thinking" (Teacher C). Teacher D commented that the students "liked the way that they were working in groups, they like working with the actual equipment." Similarly, the parents perceived that their children were no longer avoiding experimenting and now they were "happy to attempt complex problem solving" (Parent A). Parent B was delighted with the program and made the following comment:

"I like the pack and the trigger questions." To create an understanding of the bigger picture and intent. I like the idea of getting kids comfortable with failure as opposed to, "I got it wrong." "Also prompting them to come up with questions rather than just absorbing and receiving information which is the typical academic life."

The teachers found that there were "more girls [than previous years] are [were] showing an interest and positive response to STEM activities' (Year 5/6 Teacher E)" and "now girls have [had] an understanding that engineers have many different roles depending on who they are helping" (Teacher B). Teacher A joyfully made the following conclusion:

"Our Year 5 and 6 team won the XXX competition (using Lego Mindstorms) this year too, with more girls applying than previous years."

Likewise, Parent C of a female student noticed her daughter was "now looking at failure as part of the journey to be documented and telling the story, not just the answer." Parent D happily expressed that her daughter was "doing something different, out of her comfort zone."

#### 6.1.3 Increasing engagement in STEM activities: from teachers' interview and parents' survey

Another significant attitude change the teachers observed was the increase in engagement in STEM activities. They acknowledged that, "students who have low engagement in the classroom were engaged in the STEM activities" (Year 5/6 Teacher E). They indicated that "a lot of students accelerated their engagement particularly those who are in the lower quartile of my [their] class" (Year 5/6 Teacher B). They also realized "those in the lower quartile were able to apply themselves differently to normal and showed improvements in a variety of areas; they built up their confidence with STEM and the resources provided to them" (Teacher A). Teacher E (of Year 5/6) expressed that "a student who was injured turned up to school on the STEM day even though his parent gave him the option to stay home." Teacher C made this final comment on student engagement: "generally, the whole cohort looked forward to Fridays and they actually looked forward to that session!" Similarly, Parent E of a female student described that her daughter was "very engaged and excited about STEM and the opportunities so I [she] have bought her a STEM kit for her upcoming birthday." Parent F of a male student expressed that his son had "excitement about practical use of his invention."

#### 6.1.4 Improvement in problem solving skills: from teachers' interview and parents' survey

Another significant change that the teachers observed was students' improvement in problem solving skills, which was out of the teachers' expectation. They also "noticed an improvement in the ability to generate and explain their ideas" (Year 5/6 Teacher E). Teacher C made the following comments regarding students solving their problem on their own:

"You have the ability to look something and then the code, for example with the robotics, the robot is not working and not doing what they thought the program actually enabled them to do and then going back and tracing back where the areas are in the code and identifying it. And I think the surprise on their face or just that self-accomplishment is the fact that they have actually solved that problem on their own and then all of a sudden, the robots' working."

Parent F also noticed this improvement. One parent expressed that she was aware of her daughter's "increased ability of critical thinking."

### 6.2 Teachers' perception change in teaching STEM—Mentoring and networks

One of the interview questions that explored the teachers' perception of the crucial factor for successfully integrating engineering into Science curriculum shed light into the importance of the community of practice and support from industry. All the five interviewed teachers agreed that the resources sponsored by industry, the university and the state Department of Education as well as the assistance of the project mentors were definitely the assets of the program. Teacher D gratefully expressed that "the mentors played a crucial role in guiding students through the tasks and their approachable nature and quick problem-solving skills made them invaluable in the effective running of the program." Likewise, Teacher C stated that "they [the mentors] were very hands on and engaged with students, they did really well." Teacher A of a girl school acknowledged the significant role of the female mentors and expressed: "I do think again having mentors, young women empowering young women, that's the power of this project." The teachers also recognized their knowledge and capacity in teaching STEM have been extended through working with the mentors. Teacher B made the following comment to express her appreciation:

"What would definitely keep is the mentors. That's the highlight and students being able to see and work with someone in that field that's not the teacher. That's very empowering. And the resources, can't do much without resources. And the support that you provide for students and teachers in delivering and building capacity and knowledge and understanding in our teachers really."

Teacher E further acknowledged the contribution of mentors to the success of the program:

"I think a lot of teachers that go school, uni, don't have a lot of opportunity to learn beyond the classroom, and I think that's probably the biggest problem. I think what we need to see is a lot of people from industry coming into the education profession, and improving the education profession. The National Employment Services Association of Australia has been to create just to support its existence. I think that we need to bring people from industry and from the professions that run this sort of stuff into schools and if we do that we'll kick some goals. . ..”

Making the final remark, Teacher E expressed that many science teachers had the right intentions but did not have the skillset for teaching STEM in schools. He urged the school Principals to involve mentors and role models from universities and industries in the STEM teaching process to develop teachers' relevant skillset and knowledge.

## 7 Discussion

The hands-on STEM × Play program using engineering design process found students' positive perception change about STEM from the perspectives of students, families and teachers. There was evidence of positive learning outcomes for students, including critical skills needed for STEM professions such as comfort with failure (including learning by trial by error), collaboration, critical thinking and problem solving. Future work could involve evaluation of students' STEM knowledge and skills.

Core to the program's design was the community of practice that provides teachers with relatable university student and industry role models and mentors that support their teaching and learning process. The mentors were found to be a key factor in leading to positive perception change about teaching STEM among the participating teachers. This was particularly evidenced in the feedback from teachers. However, the learning process of mentors, the impacts on their career as well as on the local community of practice after mentoring the school students were not investigated. In the future, mentors and the community of practice could be involved in the evaluation process.

Finally, the program aimed to build teachers' capacity to teach STEM and the results indicated that the approach of in-classroom, co-facilitation of the engineering design process as a tool to integrate STEM in primary school could help to remove barriers for teachers to trying new pedagogical approaches. Combined with the community of practice, teachers helped facilitate and managed the student learning, whilst building capacity about STEM skills and technologies with mentors' support. Evidencing this successful approach is support from teachers for continual engagement with the community of practice to support STEM learning, including extending to other year levels post-program. Based on the Theory of Change, these positive perception changes, if sustained could result in long-term impact through further engagement in STEM study and careers.

## 8 Conclusion

A lack of teaching and learning resources to support STEM teaching (Roehrig et al., 2012) is one of the crucial barriers to promoting STEM education in schools. To complement this program's structure around the engineering design process was university STEM student and industry project mentors, and STEM resources supported by industry, the university and the state Department of Education that helped to upskill teachers' STEM skills. Thus, future work can focus on how to better connect STEM teachers to industry and other participating and local schools so that teachers can eventually become part of the community of practice in engineering for enhancing their STEM knowledge and teaching.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

The studies involving humans were approved by the University of Technology Sydney Australia. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation in this study was provided by the participants' legal guardians/next of kin. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

ML: Formal analysis, Writing – original draft, Writing – review and editing, Conceptualization, Investigation. EC: Conceptualization, Methodology, Resources, Writing – review and editing, Investigation.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Models of classroom assessment for course-based research experiences

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Course-based research pedagogy involves positioning students as contributors to authentic research projects as part of an engaging educational experience that promotes their learning and persistence in science. To develop a model for assessing and grading students engaged in this type of learning experience, the assessment aims and practices of a community of experienced course-based research instructors were collected and analyzed. This approach defines four aims of course-based research assessment—(1) Assessing Laboratory Work and Scientific Thinking; (2) Evaluating Mastery of Concepts, Quantitative Thinking and Skills; (3) Appraising Forms of Scientific Communication; and (4) Metacognition of Learning—along with a set of practices for each aim. These aims and practices of assessment were then integrated with previously developed models of course-based research instruction to reveal an assessment program in which instructors provide extensive feedback to support productive student engagement in research while grading those aspects of research that are necessary for the student to succeed. Assessment conducted in this way delicately balances the need to facilitate students' ongoing research with the requirement of a final grade without undercutting the important aims of a CRE education.

KEYWORDS

course-based research experience (CURE), science education, assessment, intergrated research and education community (iREC), grading

## Introduction

Recent educational initiatives in STEM are facilitating wide-spread implementation of course-based research experiences (CRE) because they increase persistence for students across many demographics (Russell et al., 2007; Jordan et al., 2014; Hanauer et al., 2017; Hernandez et al., 2018). This educational approach is characterized by having students involved in conducting and contributing to authentic scientific research projects (Hanauer et al., 2006, 2012, 2016, 2017; President's Council of Advisors on Science and Technology, 2012; Graham et al., 2013; Auchincloss et al., 2014; Hanauer and Dolan, 2014; Hernandez et al., 2018). Recent research on the pedagogical approach to teaching a CRE describes how this educational design transitions the ways in which instructors teach and the way in which the relationship between the instructor and the student is conceptualized and manifest (Hanauer et al., 2022). In particular, the hierarchy which is so prevalent in most educational settings is flattened slightly with the instructor and student working together on a shared research project (Hanauer et al., 2022). The expertise of the instructor is utilized in supporting a research process, the outcomes of which are not necessarily known (Auchincloss et al., 2014). For both instructor and student, the research is on-going and to a degree unpredictable. Timing for various outcomes may vary across students and projects, the type of interaction and expertise that the instructor has to provide may change and broadly the instructor and student need to be flexible in the ways in which they interact around the emerging scientific work. Hanauer et al. (2022) describe in detail the nature of this pedagogy and the ways in which instructors work with students in teaching a CRE.

While the pedagogical implementation of a CRE transitions the relations between instructor and student, the institutional requirement for a grade has not changed. Classroom grading is a significant and ubiquitous practice in STEM education in general and is a requirement whether the class is a CRE or not. The specific nature of a CRE raises several problems in relation to classroom grading. How does a teacher maintain the process of "shared" scientific research that is important beyond the classroom, if the instructor is "grading" the student on in-class tasks? When the nature of a class is not dictated by delimited content knowledge or a prescribed set of skills, what are the aims of assessment within a CRE? How does an instructor support and encourage a student during the challenges and potential failures of authentic science, if both student and instructor know that they need to assign a grade for the work being conducted? Broadly the problem of assessing and grading students in a CRE is that the CRE aims to provide a professional, authentic research experience in which the student feels that they are scientists. Grading seems quite artificial in this particular educational design.

Prior approaches to assessing a student's scientific inquiry divide into two camps: analytic schemes and authentic task modeling. Early work used an analytic scheme to define the components of scientific inquiry and suggested methods for assessing each of the parts in isolation. For example, Zachos (2004) delineates the core capabilities of scientific inquiry to include coordinating theories, searching for underlying principles, being concerned with precision, identifying sources of error in measurement and proportional reasoning, and suggest these should be used in the design of a series of performance tasks. Wenning (2007) designed a multiple-choice test of the components of a scientific inquiry such as identifying a problem, formulating a hypothesis, generating a prediction, designing an experiment, collecting and organizing data, using statistical methods, and explaining results. Shavelson et al. (1998) proposed using a range of performance tasks to evaluate scientific inquiry abilities of students. In line with this analytic approach, Pelaez et al. (2017) specified a set of core experimentation competencies consisting of the categories—identify, question, plan, conduct, analyze, conclude, and communicate. Zelaya et al. (2022) categorize 14 survey style instruments and 16 evaluation rubrics in relation to this set of competencies specifying the degree of overlap between each tool and the specified competencies. Similarly, in an extensive review of the existing tools that can be used for the assessment of a CURE, Shortlidge and Brownell (2016) review 26 survey style tools that can be used to assess different aspects of the research experience such as critical thinking, views of science, project ownership, biological concepts, and experimental design. What many these approaches have in common is the idea that the grading of scientific inquiry can be externalized from the actual research that the student is doing; students are evaluated for a set of skills, competencies, dispositions, and abilities for future scientific research.

The second camp proposed modeling authentic activity. In principle, if a CRE involves authentic research which produces scientific findings useful for a scientific community and the student is seen as a researcher, it would be logical that the evaluation of the student's work would be situated in the ways professional scientists are evaluated. However, practically, waiting for a paper to be published or

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a poster presented at a professional conference would be problematic both in relation to timing and the threshold level for successful student outcomes. Instead, Hanauer et al. (2009) proposed an approach termed *Active Assessment* which analyzes the professional research practices of a specific research project and then uses these as a way of generating a rubric for evaluating student work. Assessment is done on the student as they work through the scientific inquiry they are involved in. A similar approach has been proposed by Dolan and Weaver (2021). What characterizes this approach are the ideas that assessment and grading should be situated in the performance of a student while conducting research in the CRE and that this assessment should be based on professional performance.

However, while this second approach offers a conceptual basis of how assessment in a CRE could be conducted, it is not based on data from actual instructors teaching a CRE. The aim of this study is to look at how experienced instructors in a large-scale CRE program—the Science Education Alliance (SEA) program by the Howard Hughes Medical Institute (HHMI)—describe their processes of assessing their students engaged in course-based research. Working with this large community of experienced CRE instructors over a 2-year period, models of CRE assessment were developed. In addition, this current paper builds upon prior research on models of CRE instruction, which were similarly developed with this community of SEA instructors (Hanauer et al., 2022). The outcome of this study thus provides insight into how CREs can be assessed and graded while maintaining the pedagogical approach designed to provide an authentic research experience for students and enhance persistence.

## Issues with assessment and grading

In a classic text, Walvoord and Anderson (1998) specify a series of basic roles that grading is expected to perform: (1) It should be a reliable measure of a student's performance of required work; (2) It should be a means of communicating the quality of the student's performance with parents, other faculty, the university, future institutions, and places of work; (3) It should be a source of motivation; (4) It should provide meaningful information for feedback to students and instructors to enhance learning; and (5) It can be a way of organizing class work. However, as seen in the scholarship, the implementation of grading is not unproblematic.

As documented over decades, there are questions as to whether grading always fulfills the stated aims above (Jaschik, 2009). Prior research has suggested that STEM faculty have the knowledge to create assessment tasks but often lack an understanding of how to validate these tasks (Hanauer and Bauerle, 2015). Some faculty problematically assume that the way they were graded is a basis for the grading of their own students leading to a persistence of outdated assessment practices (Boothroyd and McMorris, 1992). When considering what to assess and grade, there can be confusion between learning components tied to stated learning objectives of the course and other aspects of being a student such as punctuality, attendance, and participation (Hu, 2005). Additionally, there is little agreement between instructors as to which components should go into a grade with different instructors varying greatly in relation to how assessment is conducted (Cizek et al., 1996). Research has also shown that grades can vary in relation to variables such as instructors, departments, disciplines, and institutions (Lipnevich et al., 2020) and in relation to specific student characteristics such as physical attractiveness (Baron and Byrne, 2004) and ethnicity (Fajardo, 1985).

It is important to understand the central role grading plays in the lives of students. Grading can increase anxiety, fear, and lack of interest and hinder the ability to perform on subsequent tasks (Butler, 1988; Crooks, 1988; Pulfrey et al., 2011). There are alarming rates of attrition from STEM documented for students who identify as African American or Black, Latino, or Hispanic, and American Indian and Alaska Native (National Science Board, 2018; Asai, 2020; Whitcomb and Chandralekha, 2021) and low grades is one of the factors that leads to this outcome (Whitcomb and Chandralekha, 2021). The relationship between grading and persistence is situated in the effect of negative feedback on performance (such as a lower-than-expected grade) and the individual's sense of self-efficacy in that field (Bandura, 1991, 2005). Students who identify as African American or Black, Latino or Hispanic, and American Indian and Alaska Native may enter the STEM fields with pre-existing fears and anxieties about their work resulting from stereotype threat (Hilts et al., 2018). Negative experiences with grading further exacerbate these feelings leading to a disbelief in their ability to continue in STEM and hence attrition from that course of study (Hilts et al., 2018; Whitcomb and Chandralekha, 2021). Recent research has shown that grading works in two parallel ways: lower grades limit the opportunities that are available to students and increase the negative psychological impact on students' intent to persist in STEM (Hatfield et al., 2022). As such grading, if not conducted appropriately, could directly undermine the main aim of a CRE—increased persistence in STEM for all students.

# Methodology

## Overview

A multi-method, large-scale and multi-year research methodology was employed in this study. Data collection and analysis was conducted over a 2-year period in a series of designed stages with full participation from a large group of CRE instructors and a dedicated science education research team. The project developed in the following stages:

1. *Survey*: The initial stage of the study involved a qualitative and quantitative survey. The qualitative section asked about grading and assessment procedures used by instructors in their CRE courses and asked for a detailed explanation of the way these were used in their courses. The quantitative section used the psychometrically validated scales of the Faculty Self-Reported Assessment survey (Hanauer and Bauerle, 2015) to evaluate the knowledge level of the surveyed faculty. The aim of this first stage of the project was to collect descriptive data on the participants' understanding of assessment and specific information on the way they conduct assessment and grading in their courses.
2. *Analysis and large-scale community checking of assessment aims and practices*: Data from the qualitative study were analyzed using a systematic content analysis process, and the quantitative data were analyzed using standard statistical procedures. The quantitative data was analyzed in terms of high-level assessment aims and specific grading and assessment practices.

All analyses were summarized and then presented in a workshop setting to a cohort of 106 CRE instructors. In a small-focus group format, the aims and practices were presented and instructors provided written feedback on the validity of the analysis, the specification of the high-level aims, the specification of practices, and the assignment of the practices to assessment. Instructors responded within the workshop and were subsequently given an additional week to provide online responses to the questions posed. All data were collected using an online survey tool.

3. *Analysis and community checking of models of assessment and grading*: Data from the first stage of community checking were analyzed for modifications to the assessment aims and the assigned assessment and grading practices. Percentage of agreement with the aims and practices was calculated and modifications to the models were assigned. During this analysis there were no changes to the high-level aims, but several specific practices were added. Once the table of aims and practices had been finalized, the original survey commentary dealing with how assessment and grading were conducted was consulted. Using this commentary and the pedagogical models of CRE instruction (Hanauer et al., 2022), the aims and practices of assessment were integrated with the discussion of CRE instruction. Three integrated models were developed and presented to a dedicated group of 23 instructors for validation process. Instructors were asked to provide feedback on the quality and descriptive validity of the models, the specification of aims of assessment and the specific practices. Instructors provided feedback during the workshop and for a week after the workshop. All data were collected using an online survey tool.
4. *Finalization of the models*: Feedback from the workshop was analyzed for verification of the models and any required modifications that might be needed. Agreement with the models and their components were checked. Following this process, the models were finalized.

## Participants

Participants for this study were elicited from the full set of instructors who teach in the SEA program. The SEA program is a large-scale, two semesters, program implemented at 190 institutions predominantly with Freshman and Sophomore students. This course is supported by the Howard Hughes Medical Institute and has scientific support from the Hatfull laboratory at the University of Pittsburgh. For the first stage of data collection, a survey request was sent to 330 SEA instructors. 105 faculty responded with 72 instructors providing full answers on the survey. Table 1 presents the instructor demographics. The SEA faculty respondents are predominantly White (≥58.1%) and women (≥49.5%). A range of academic ranks from instructor to full professor were represented in the sample. As seen in Table 1, the majority of respondents had at least 3 years of teaching in the program and above 6+ years of teaching postsecondary science. Respondents for the community checking of the model were drawn from the SEA faculty. For each stage, 100+ instructors participated. Demographic data were not collected on the participants at the two community checking sessions. As a community of CRE instructors, during the semester, the SEA has a weekly 1-h, Friday afternoon session providing scientific and educational instructor development. During the Fall 2022 semester, two sessions were conducted by the Lead Assessment Coordinator of the SEA (Dr. Hanauer) dedicated to the development of a meaningful assessment approach. The sessions involved a lecture approach of general principles of assessment including constructive alignment between objectives and instruments, active assessment instruments that could be used and ways of interpreting outcomes. Participation in these Friday sessions were voluntary. Approximately 50 faculty attended these two sessions.

TABLE 1 Instructor demographic characteristics ($N = 105$).

| Category | Frequency | Percentage |
|---|---|---|
| *Gender* | | |
| Man | 19 | 18.10% |
| Woman | 52 | 49.50% |
| Unlisted | 1 | 1% |
| Missing | 33 | 31.40% |
| *Ethnicity identification* | | |
| Asian | 4 | 3.80% |
| African American | 3 | 2.90% |
| Hispanic/Latino | 3 | 2.90% |
| White | 61 | 58.10% |
| Multiple | 1 | 1% |
| No Response | 35 | 33.30% |
| *Rank* | | |
| Adjunct Professor | 2 | 1.90% |
| Assistant Professor | 18 | 17.10% |
| Associate Professor | 20 | 19% |
| Full Professor | 17 | 16.20% |
| Instructor | 13 | 12.40% |
| Other | 2 | 1.90% |
| Missing | 33 | 31.40% |
| Years teaching in the SEA | | |
| 1 | 12 | 11.40% |
| 2 | 14 | 13.30% |
| 3 | 13 | 12.40% |
| 4 | 12 | 11.40% |
| 5 | 4 | 3.80% |
| 6 + | 17 | 16.20% |
| Missing | 33 | 31.40% |
| Years teaching postsecondary science | | |
| 2 | 3 | 2.90% |
| 3 | 5 | 4.80% |
| 4 | 8 | 7.60% |
| 5 | 9 | 8.60% |
| 6+ | 47 | 44.80% |
| Missing | 33 | 31.40% |

## Instruments

As described in the overview of the research process, data collection consisted of a qualitative and quantitative initial survey, followed by a large community checking survey and a final assessment model checking survey. A specific tool was developed for each of these stages. The original survey consisted of three sections:

1. *Familiarity with assessment terms*: The first set of items were from the psychometrically validated Faculty Self-Reported Assessment survey (Hanauer and Bauerle, 2015). The survey consists of 24 established terms relating to assessment, organized into two components—assessment program and instrument knowledge, and knowledge of assessment validation procedures. On a five-point scale of familiarity (1 = I have never heard this term before; 5 = I am completely familiar with this term and know what it means), faculty rated each of the terms in relation to their familiarity with the term. The FRAS is used to evaluate levels of experience and exposure of faculty to assessment instruments and procedures. See Table 2, for a full list of the assessment terms used.
2. *Qualitative reporting of student assessment:* The second set of items were qualitative and required the instructor to describe the way in which they assess students in the SEA program, to specify the types of assessment used (such as quiz, rubric… etc.), and to explain what each assessment is used for. Following the first question, faculty were asked to describe how they grade students and what goes into the final grade. Answers consisted of written responses.
3. *Self-efficacy assessment scales*: The third set of items consisted self-reported measures of confidence in completing different aspects of assessment. The 12 items were taken from the FRAS (Hanauer and Bauerle, 2015) and consisted of a set of statements about the ability to perform different aspects of the assessment process (see Table 3 for a full list of the statement). All statements were rated on an agreement scale (1 = Strongly Disagree, 5 = Strongly Agree).

In order to collect verbal responses during the community checking stage of this project, participants completed an online survey that was presented following a shared online session in which the analyses of the main aims of assessment and the associated practices were presented (see Table 3). The survey asked for a written response to the following questions relating to each of the specified aims and associated practices:

1. Does this assessment aim make sense to you? Please specify if you agree or disagree that this is an aim of your CRE assessment.
2. For this aim, do the practices listed above make sense to you? Please comment on any that do not.
3. For this aim, are there practices of assessment that are not listed? If so, please list these additional practices and describe what these practices are used to evaluate.
4. Are there aims of assessment beyond the 4 that are listed above? If so, please describe any additional aims of assessment below.

The final community checking procedure involved the presentation of the full models of assessment to the collected participants in a shared online session (see Figures 1–3). Following the presentation of the models, the participants were divided into groups and each group was assigned a model to discuss and respond to. Each model was reviewed by two groups, and all responses were collected using an online written survey with the following questions:

1. For each of the instructional models, have the appropriate assessment aims been specified?
2. For each of the instruction models, have the appropriate assessment practices been specified?
3. Overall, do the models present an accurate and useful description of grading practices in the SEA?
4. Please suggest any modifications and comments you have on the model.

TABLE 2 Mean and standard deviation for assessment knowledge levels ($n$ = 72).

| Assessment term | Mean | Std |
|---|---|---|
| Program and instrument | | |
| Assessment program | 4.15 | 1.016 |
| Student learning outcomes | 4.89 | 0.358 |
| Student competencies | 4.67 | 0.605 |
| Formative assessment | 4.53 | 0.903 |
| Summative assessment | 4.50 | 0.964 |
| Portfolio | 4.22 | 0.982 |
| Assessment task | 4.27 | 0.878 |
| Performance assessment | 4.03 | 1.000 |
| Authentic assessment | 3.24 | 1.204 |
| Alternative assessment | 3.42 | 1.017 |
| Problem solving questions | 4.79 | 0.555 |
| Scenario questions | 4.57 | 0.766 |
| Rubrics | 4.92 | 0.278 |
| Analytic scales | 3.46 | 1.067 |
| Grand mean | 4.26 | 0.55 |
| Assessment validation | | |
| Assessment validity | 3.66 | 1.068 |
| Item discrimination | 3.11 | 1.228 |
| Assessment reliability | 3.65 | 1.103 |
| Content validity | 3.25 | 1.230 |
| Item difficulty | 3.91 | 1.126 |
| Inter-rater reliability | 3.10 | 1.503 |
| Intra-rater reliability | 3.01 | 1.468 |
| Internal consistency | 3.01 | 1.409 |
| Grand mean | 3.34 | 0.35 |

## Procedures

Data were collected in three stages. The initial stage consisted of an online survey that was distributed to all faculty of the SEA using the web-based platform Qualtrics. Following the informed consent,

TABLE 3 Faculty assessment confidence levels ($n = 72$).

| Confidence category | Mean | Std. |
|---|---|---|
| I am confident in my ability to define the important components of my course | 4.47 | 0.6 |
| I am confident in my ability to define my course is terms of student learning outcomes | 4.43 | 0.65 |
| I am confident in my ability to design formative assessments | 4.08 | 0.92 |
| I am confident in my ability to evaluate the quality of the assessments that I have designed | 3.88 | 0.75 |
| I am confident in my ability to analyze the formative assessments that I have designed | 3.72 | 0.89 |
| I am confident in my ability to analyze the summative assessments that I have designed | 3.81 | 0.97 |
| I am confident in my ability to provide students with relevant feedback based on the formative assessments that I have designed | 4.10 | 0.86 |
| I am confident in my ability to explain to specific students the outcomes of their summative assessment performance | 3.93 | 0.99 |
| I am confident in my ability to report assessment outcomes to administrators | 3.87 | 0.95 |
| I am confident that my assessments accurately reflect the teaching objectives of my course | 4.11 | 0.74 |
| Overall, I am confident in my ability to assess my students appropriately | 4.26 | 0.65 |
| I am satisfied with my current grading procedures | 4.07 | 0.79 |
| Overall | 4.04 | 0.65 |

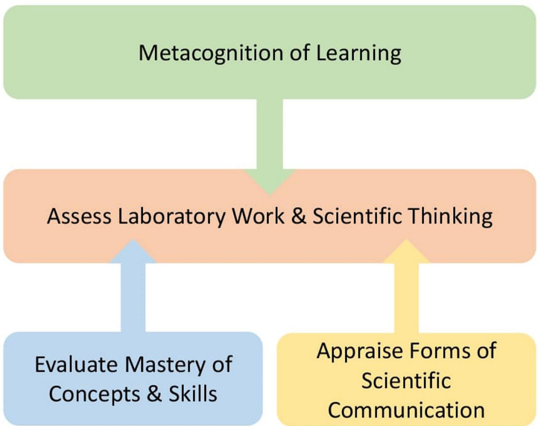


FIGURE 1
The core components of a CRE assessment model: based on the qualitative analysis of faculty descriptions of their assessment and grading practices in a CRE, four central aims of assessment were defined: (1) Assess Laboratory Work and Scientific Thinking; (2) Evaluate Mastery of Concepts, Quantitative Thinking, and Skills; (3) Appraise Forms of Scientific Communication; and (4) Metacognition of Learning. Together these four aims and associated assessment and grading practices define the assessment program of a CRE.

process responses to the qualitative and quantitative items were recorded. The second stage involved the collection of community checking data from SEA instructors. A dedicated online Zoom session was arranged for this during one of the monthly virtual faculty meetings organized through the SEA program. During a 1-h session, the analysis of the aims of assessment and the associated practices were presented to the faculty. In small groups (breakout rooms), each of the aims and its associated practices were discussed. Following the session, an online survey was sent to faculty to collect their level of agreement with the aims and practices that were presented. They were also asked to modify or add any aims or practices that had been missed in the presented analysis of the original survey. The third stage of community checking data analysis consisted of a second online session during the regular end-of-week faculty meeting. During a 1-h session, each of the assessment models was presented to the faculty who then discussed them in small groups (breakout rooms). A survey was sent to the faculty during the session to respond to the models and write their responses to the models. All data were collected in accordance with the guidelines of Indiana University of Pennsylvania IRB #21-214.

## Analysis

The analysis of the data in this study was conducted in four related stages. The initial survey had both quantitative and qualitative data. The quantitative data was analyzed using established statistical descriptive methods. The qualitative verbal data consisted of a series of written statements relating to the practices used for assessment by the different instructors and the aims of using these practices. Using an emergent content analysis approach, each of the instructor statements was analyzed and coded. Two different initial code books were developed. One dealt with the list of practices used by the faculty; the second involved the explanation of why these practices were used and what the instructor was trying to assess. The data were coded by two trained applied linguistic researchers and following several iterations, a high level of agreement was reached on the practices and aims specified by the instructors. The second stage of this analysis of the verbal survey data consisted of combining the aims and practices codes. The specified practices across all of the instructors for each of the aims was tabulated. A frequency count of the number of faculty who specified each of the practices was conducted. The outcome of the first stage of analysis was a statistical description of the levels of knowledge and confidence of faculty on assessment issues and the specification of four main aims of assessment with associated assessment practices.

The second stage of analysis followed the presentation of the tabulated coded data from the original survey to participants. In this stage of community checking, faculty specified agreement (or disagreement) with the assessment aims and the set of associated

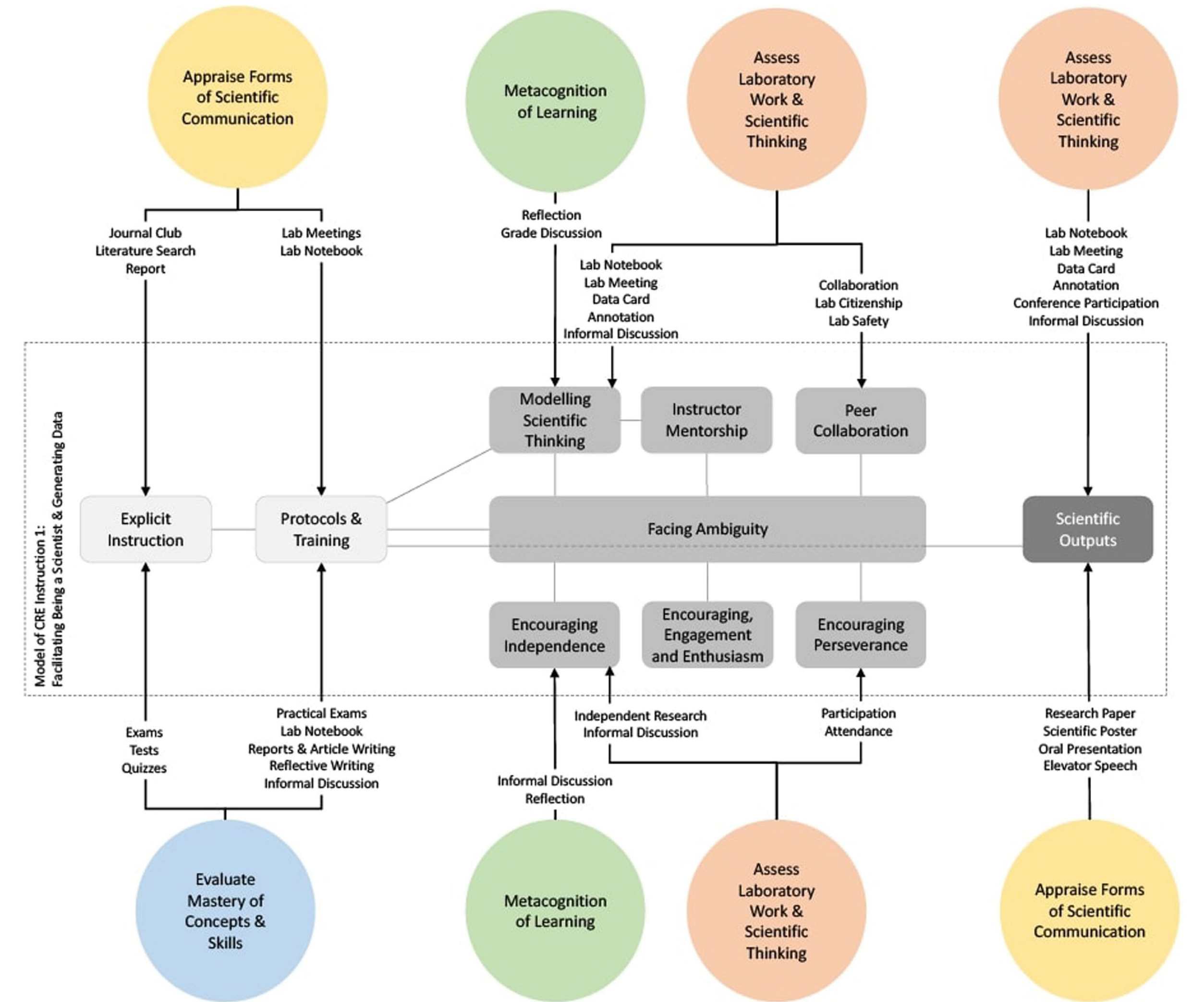


FIGURE 2
Assessing being a scientist and generating data: this model has three distinct stages. The first stage relates to the assessment of implicit instruction and protocol training. The second stage relates to aspects of doing science in the laboratory and the final stage relates to scientific outputs. The model presents the aims and practices of assessment applied at each of these stages.

practices. The verbal responses were analyzed by two applied linguistics researchers and modifications were made to the tabulated data. The degree of agreement with each of the aims and associated practices was counted. Any additional practices specified by faculty were added to the model. No new aims were specified and as such no changes were made. The table of assessment aims and practices was finalized.

Having established the aims of assessment and related practices, a third stage of analysis involved integrating the emergent assessment aims and practices with models of CRE instruction which had been previously defined for the SEA instructors (see Hanauer et al., 2022 for full details). A team of two researchers worked together to specify the points of interaction between the instructional and assessment components of CRE teaching. Using the qualitative data of the original models and the verbal statements of aims for the assessment data, integrated models of assessment were developed. Following several iterations, three assessment models corresponding to the instructional models were specified.

The final stage of analysis followed the presentation of the models of assessment to the community of SEA faculty. A team of two researchers went over the changes presented by faculty in relation to each of the models. Changes that were specified, such as the addition of specific practices into different models, were made. The outcome of this process was a series of three models that capture the aims and practices of assessment.

## Results

### Instructor familiarity and self-efficacy with assessment

To build models of CRE assessment based on qualitative reports from instructors in the SEA program, we first evaluated instructors' knowledge of assessment terms and their confidence in implementing assessment tasks. For instructor knowledge of

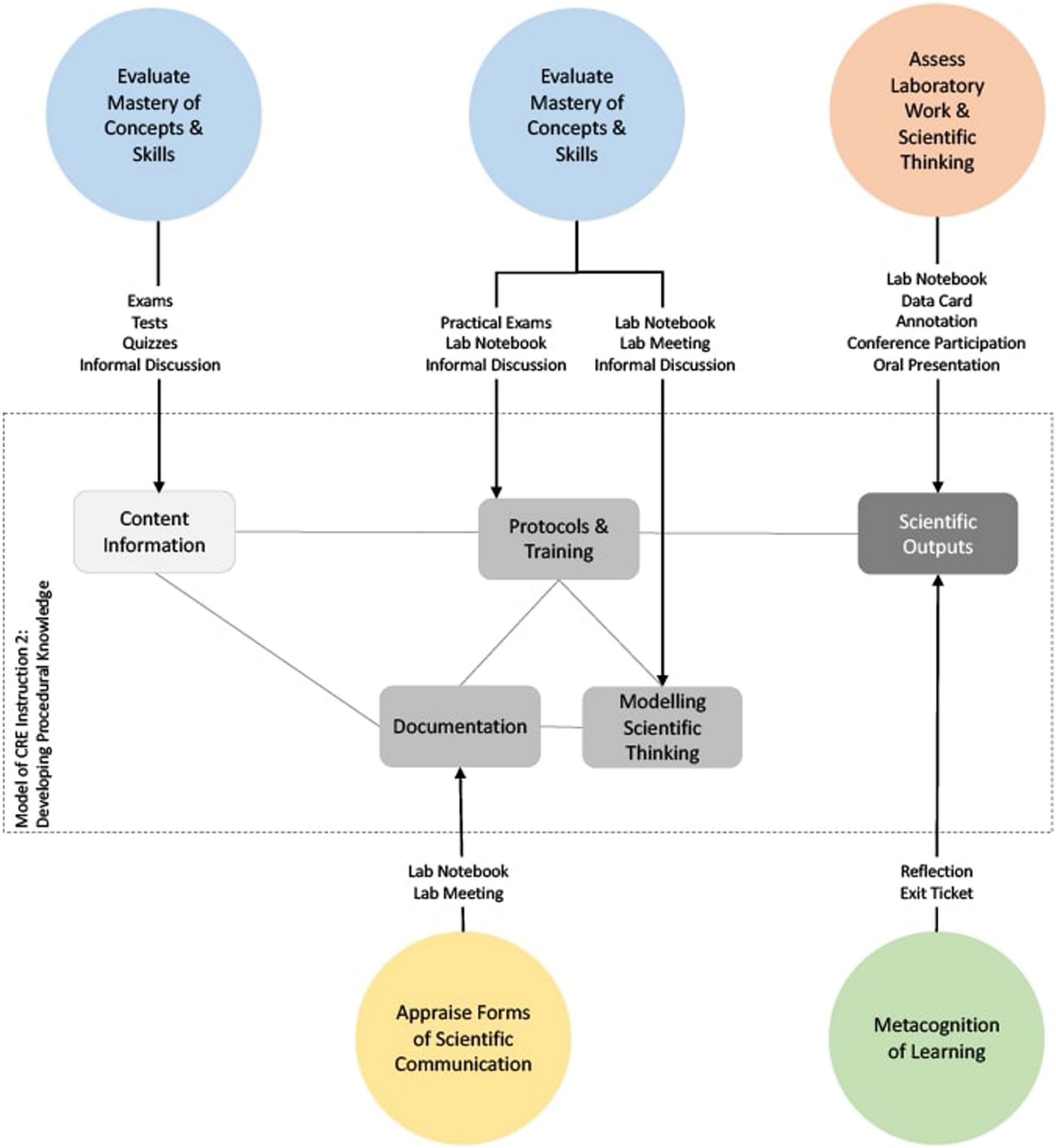


FIGURE 3
Assessing procedural knowledge: this model has three distinct stages. The first stage relates to content information. The second stage relates to protocol training and training a student to think like a scientist. The third stage relates to scientific outputs. The model presents the aims and practices of assessment applied at each of these stages.

assessment, we utilized the Faculty Self-Reported Assessment Survey (FRAS; Hanauer and Bauerle, 2015)—a tool which measures two components of assessment knowledge: (1) knowledge of assessment programs and instruments and (2) knowledge of assessment validation. Internal consistency was calculated for the each of the FRAS components. Cronbach's Alpha was 0.86 for the Knowledge of assessment programs and instruments components and 0.94 for the knowledge of assessment validation component. These levels suggest that each of the components is sufficiently consistent and hence reliable.

For the Program and Instrument component, instructors reported high levels of familiarity (Scale = 1–5, Grand Mean = 4.26, Std. = 0.55). All items were above 4 (high level of familiarity), except for the terms related to performance assessment. These latter terms, which include Alternative Assessment and Authentic Assessment, were nevertheless familiar to instructors (above 3). The Validation components of the survey, which addresses terms relating to the evaluation and quality control of assessment development, were also familiar to instructors (Grand Mean = 3.34, Std. = 0.35). This result is in line with prior studies of faculty knowledge of assessment terms (Hanauer and

Bauerle, 2015). The results overall for the two dimensions suggest that instructors in this study have the required degree of assessment understanding to be reliable reporters of their assessment procedures and activities.

To augment the FRAS data, self-efficacy data were collected on instructors' confidence in completing assessment related tasks. Internal consistency was calculated for the self-efficacy scale. Cronbach's Alpha was 0.93 which shows that this scale is reliable As shown in Table 3, instructors reported high levels of confidence in their assessment abilities (Scale = 1–5, Grand Mean = 4.04, Std. = 0.65). The highest confidence was in relation to defining important components of their course and student learning outcomes, while the lowest levels of confidence were in relation to the ability to evaluate, analyze and report on their assessments. The confidence levels for the latter were still relatively high (just below 4) and reflect, to a certain extent, the same trend as seen using the FRAS instrument. Taking into consideration the results of the FRAS and self-efficacy tasks, instructors report moderate to high levels of assessment expertise and confidence, which suggest that these instructors have the required expertise to report and evaluate the aims, practices, and models of CRE assessment.

## Aims and practices of CRE assessment

A fundamental goal of this study was to describe the aims and practices of experienced CRE instructors for assessing students in a CRE. As described in the methodology section, a list of aims and practices for assessment was elicited from the written survey data completed by instructors in the HHMI SEA program, which was then community-checked and modified. The faculty were asked to describe how they assess students in the SEA program what types of assessment used (such as quiz, rubric…etc.), and to explain what each assessment is used for. The aims specified by the faculty reflected components of pedagogical activity that came together while teaching a CRE. So, for example, assessing the physical work of lab was integrated with scientific thinking as a single aim. Broadly the aims reflected work in the laboratory, aspects of mastery, communication and student self-evaluation of their learning.

Four central aims of CRE assessment were defined. For each aim, there were a cluster of assessment practices that were employed to assess student learning, with different instructors utilizing different subsets of these practices. The aims of CRE assessment, the practices related to each of the aims, and the degree of agreement among faculty for each aim and set of practices are presented in Table 4 and described below:

1. *Assess laboratory work and scientific thinking:* The objective of this assessment aim was to assess a student's readiness, in terms of their practices, thought patterns and ethics, to function as a researcher in the laboratory setting. As seen in Table 4, several different practices were related to this aim, which include (1) assessing student behaviors such as participation, attendance, citizenship, collaboration, safety and independence, and (2) assessing students' scientific thinking based on their lab notebooks, data cards, independent research, conference participation, and informal discussion. During the community checking stage, 85.95% of the faculty specified that this category was an aim of their assessment program and that the assigned practices were appropriate.
2. *Evaluate mastery of concepts, quantitative thinking, and skills*: The objective of this assessment aim was to assess the underpinning knowledge and skills that students need in order to function successfully, as a researcher, in the CRE laboratory setting. The practices related to this assessment aim include (1) the checking of laboratory techniques and skills using practical exams and lab notebooks, (2) the evaluation of required scientific knowledge through exams, tests, quizzes, written reports, and articles, and (3) the assessment of quantitative knowledge. During the community checking stage, 80.99% of faculty specified that this category was an aim of their assessment program and that the assigned practices were appropriate.
3. *Appraise forms of scientific communication*: The objective of this assessment aim was to evaluate the ability of students to convey their research and attain scientific knowledge through the different forms of science communication. The practices related to this assessment include (1) oral abilities such as oral presentation, peer review, lab notebook meetings, scientific poster, and elevator speech, and (2) literacy abilities such as reading and writing a research paper, report writing, notebook writing, scientific paper reading, literature review, and poster creation. 63.64% of faculty specified that this category was part of their assessment program.
4. *Metacognition of learning*: The objective of this assessment aim was to assess the ability of students to regulate and oversee their own learning process. This aim is based on the assumption that being in control of your learning process improves the ability to learn. The practices related to this aim include reflection, discussion and an exit ticket. 76.85% of faculty specified that this category was part of their assessment program.

These four aims and associated practices define a program of assessment for CRE teaching. As depicted in Figure 1, the central aspect of an assessment program for a CRE is to evaluate the ability of a student to work and think in a scientific way. This central aspect is supported by two underpinning forms of knowledge: (1) mastery of concepts, quantitative thinking, and skills and (2) the ability to communicate science. Overseeing the whole process is metacognition, which allows the student to regulate and direct their learning process. Accordingly, information on the students' functioning across all these areas are collected as part of the assessment program.

## Models of assessment in a CRE

The assessment program presented in this study is implemented by instructors in conjunction with a program of CRE instruction that has been previously described (Hanauer et al., 2022). The assessment aims and practices described here can therefore be integrated with the aims and practices (or models) of CRE instruction. The stated aims of

TABLE 4 Assessment aims and practices with frequency of mentions and definitions.

| Aims of assessment | Practices | Frequency | Practice definition (Evaluation of…) |
|---|---|---|---|
| Assess laboratory work and scientific thinking: (Skills, practices, thoughts patterns, and ethics related to laboratory work) | Lab meeting | 12 | Check current status of student research |
| | Lab notebook | 63 | Student's ability to record their research and to evaluate research status. |
| | Data card | 9 | Document and organize data collection |
| | Annotation notebook | 5 | Note keeping of annotation process |
| | Annotation[1] | 37 | Annotation of phage genome |
| | Lab citizenship | 10 | Student behavior in the lab |
| | Collaboration | 5 | Student ability to work together with other student researchers |
| | Participation, attendance | 39 | Presence and participation of student |
| | Independent research | 9 | Check student ability to conduct bioinformatic research |
| | Conference participation | 14 | Attending a professional scientific convention |
| | Lab safety | 3 | Aseptic technique and safe behavior |
| | Informal discussion* | | *Ad hoc* on task instructor-student discussion |
| | Total | 203 | Community checking positive agreement with categories = 85.95% |
| Evaluate mastery of concepts, quantitative thinking and skills | Practical exams[2] | 20 | Check students' mastery of technical skills in related experiments |
| | Exams and tests | 22 | Students understanding of lectures, reading materials and science |
| | Quiz[3] | 72 | Students understanding of concepts (including annotation) |
| | Lab notebook* | | |
| | Reflective writing* | | |
| | Reports* | | |
| | Article writing* | | |
| | Informal discussion* | | |
| | Total | 114 | Community checking positive agreement with categories = 80.99% |
| Appraise forms of scientific communication | Research paper/Report | 46 | Students' ability to participate in writing a research paper |
| | Scientific poster | 44 | Presentation and understanding of research |
| | Oral presentation | 45 | Oral-lecture format of research presentation |
| | Peer review | 6 | Students' ability to evaluate each other's research |
| | Journal club | 16 | Shared reading of primary literature |
| | Literature search | 11 | Search for relevant scientific scholarship |
| | Informal communication | | |
| | Lab notebooks | | |
| | Lab meetings | | |
| | Elevator speech | | |
| | Total | 168 | Community checking positive agreement with categories = 63.64% |
| Metacognition of learning | Reflection | 2 | Evaluate students understanding and attitudes to learning and research |
| | Exit ticket | 10 | Checklist of activities related to research and learning |
| | Grade discussion | | |
| | Informal discussion | | |
| | Total | 12 | Community checking positive agreement with categories = 76.85% |

*Added during the community checking process (no frequency data). [1]Annotation = Annotation (28) + Bioinformatic work (3) + Group Annotation Assignment (6) = 37. [2]Practical Exams = Practical Exams (6) + Lab Practical (14) = 20. [3]Quiz = Quiz (65) + Question and Answer Assignment (7) = 72.

CRE instruction are (1) Facilitating the experience of being a scientist and generating data; (2) Developing procedural knowledge, that is the skills and knowledge required to function as a researcher; and (3) Fostering project ownership, which include the feelings of personal ownership and responsibility over their scientific research and education (Hanauer et al., 2022). These aims are directly in line with the broad aim of a CRE in providing a student with an authentic research experience (Dolan and Weaver, 2021). In the sections that follow, and using a constructive alignment approach (Biggs, 1996; Ambrose et al., 2010), the assessment aims and practices uncovered in this study are presented with the associated models of CRE instruction previously described.

## Model 1: assessing being a scientist and generating data

Being a scientist and generating novel data is a core aspect of a CRE. As shown in Figure 2 and described below, the instructional approach to achieving this aim involves three stages of instruction:

a. Stage 1 involves preparing the student with the required knowledge and procedures in order to function as a researcher who can produce usable data for the scientific community. The pedagogy employed here includes the use of explicit instruction to provide students with the foundational knowledge to understand the science they are involved with and protocol training to make sure a student can perform the required scientific task.

Accordingly, assessment in this first stage of the model is aimed at Evaluating Mastery of Concepts and Quantitative Thinking. The assessment practices used here include both exams and in class quizzes, which are well suited for this purpose. Additionally, given that this foundational scientific knowledge must often be retrieved from various forms of scientific communication, including lecture, a research paper, a poster, and an informal discussion with an expert, the ability to use scientific communication for knowledge acquisition is also evaluated. Practices such as the evaluation of a literature search report or presentation at a journal club can provide information on how the student understands and uses different modes of scientific communication. Combined, the use of exams, quizzes, literature search reports, and journal club participation can provide a rich picture of the foundational knowledge of a student as they enter the process of doing authentic research.

To assess a student's ability to use a range of specific protocol properly, instructors rely on practical exams and a student's lab notebook, which are well established ways of checking whether a student understands and knows how to perform a specific procedure. Beyond these approaches, instructors reported that they used informal discussion, reflective writing, article writing, and the lab notebook meeting to evaluate formally and informally whether the students understand how to perform the different scientific tasks that are required of them. This combination of explicit teaching of scientific knowledge and procedures, with formal and informal assessment of these abilities, serves to create a basis for the second stage of this pedagogical model, described below.

b. Stage 2 involves supporting students to manage the process of implementing procedures in order to generate authentic data. A central aspect of this stage is that the student moves from a consumer to a producer of knowledge, and this involves a change in the students' mindset concerning thinking processes, independence, perseverance, and the ability to collaborate with others. Importantly, as is the case with science, positive results are not guaranteed and students face the ambiguity of failed outcomes and unclear paths forward. It is for this reason that the pedagogy at this stage involves a range of different supportive measures on the part of the instructor. These include modeling scientific thinking, providing encouragement and enthusiasm, mentoring the student at different points and, most importantly, making sure that the students understand that the scientific process is one that is fraught with challenges that need to be overcome. A lot of instruction is provided at the time that a task or event occurs.
Assessment at this stage is covered by the aim of Assessing Laboratory Work and Scientific Thinking and the Metacognition of Learning. The scientific thinking of the student is primarily assessed through the discussion of the lab notebook, data and annotation cards, often during lab meetings. Importantly, as reported by faculty, a lot of this assessment is directed by informal discussion with the aim of providing direct feedback to the student so that they can perform the tasks that are required. This is very much a formative assessment approach with direct discussion with the student while they are working and in relation to the research they are doing. There are behaviors that faculty specify are important to track, such as participation, attendance, collaboration, lab citizenship and lab safety. These behaviors are a prerequisite for the research to move forward for the student and the research group as a whole. The use of assessment practices such as reflection and discussion allows the assessment of the degree of independence of the student, in addition to actually positioning the student as independent; the requirement of a reflection task, whether written in one's lab notebook or verbally, situates the students as the researcher thinking through what they are doing. Overall, this stage involves extensive informal formative assessment of where the student is in the process from the practical, scientific and emotional aspects of doing science, combined with a more formal evaluation of the behaviors which underpin a productive and safe research environment.

c. The third and final stage of this pedagogical model involve the actual scientific output produced by the student researcher. A CRE is defined by the requirement that data are produced that is actually useful for a broader community of scientists. If the second stage of the assessment of this pedagogical model is characterized by informal, formative assessment approaches, this final stage is characterized primarily by formal summative assessment. At this stage, the student has produced scientific knowledge and is in the process of reporting this knowledge using established modes of scientific communication. The student is assessed in relation to the knowledge they have produced and the way they communicate it. As such, both the aims of Assessing Laboratory Work and Scientific Thinking and the Appraisal of Forms of Scientific Communication are utilized. The lab notebook, data card, annotation, conference presentation, oral presentation, and poster all involve a double summative assessment approach: an evaluation of the quality of the scientific work that has been produced and an evaluation of the ability of the student to communicate this knowledge using established written and verbal modes of scientific communication. This final stage provides the opportunity for evaluating the whole of the research experience that the student has been involved in.

To summarize, the instruction and assessment model of Being a Scientist and Generating Data has three distinct stages. The initial stage is designed to make sure that the student can perform the required tasks and understand the underlying science. Assessment at this stage is important as the learning involved in this stage is a prerequisite for the second stage of the model. During the second stage, while the student is functioning as a researcher, the primary focus of the assessment model is to provide feedback to the student and the required level of expertise advice and emotional support to allow the research to move forward. This stage is characterized by informal discussion and is primarily a formative assessment approach. The final stage is directed at evaluating the scientific outcomes and the student's ability to communicate them. Assessment at this stage offers a direct understanding of the quality of the work that has been conducted, the degree to which the student understands the work, and the ability of the student to communicate it.

## Model 2: assessing procedural knowledge

Being able to perform a range of scientific procedures is a central and underpinning aspect of being a scientist and a core feature of a CRE. Figure 3 presents a pedagogical and assessment model for teaching procedural knowledge. As seen in the previous model, protocols are an important precursor that enables an undergraduate student to conduct scientific research. In model 2, how students learn scientific procedures is further explicated from model 1. As can be seen in Figure 3, there are three stages to the development of procedural knowledge.

a. The first stage involves enhancing the students' content knowledge concerning the science behind the protocol they are using and scientific context of the research they will be involved with. For a student to become an independent researcher, they need to be able to not just follow a set of procedures but also to understand the science that it relates to. The pedagogical practice involved here includes explicit instruction, discussion and reading of primary literature. From an assessment perspective, the evaluation of this underpinning content knowledge is conducted using established practices such as exams, tests, and quizzes. In addition, as reported by faculty, this material was informally discussed with students to gauge understanding of the context and role of the procedure.
b. In the second stage, students are taught how to implement the procedure and to think like a scientist. This involves using a protocol, scientifically thinking through the process of using a protocol, and appropriate documentation of the process of using a protocol. Scientific thinking at this stage includes interpretation of outcomes, problem solving, and deciding about next steps. In this way, learning a protocol is not only about being able to perform, analyze and document a procedure appropriately, but also involves the development of independence for the researcher. These two components are related in that if a student really has a full understanding of the procedure, they can also make decisions and function more autonomously. Such mastery is particularly critical in a CRE because the research being conducted is intended to support an ongoing authentic research program. As reported by faculty, there are both formal and informal assessments that facilitate this evaluation. Practical exams allow faculty to really check the performance of a particular procedure and their understanding. Lab notebook evaluation, lab meeting interactions and informal discussion about the work of a student as they perform certain tasks provides further evidence of the student's mastery of the concepts and skills that are involved. These interactions are primarily formative and have the aim of providing feedback for the improvement of the student's understanding of scientific procedures.
c. An additional level of assessment at this stage relates to the ability of students to document their research in the lab notebook, explain their research in a lab meeting and to converse with peers and instructors about what they are doing. These are all aspect of scientific communication, and assessment at this second stage of learning procedural knowledge includes the aims evaluating mastery of concepts and skills and of an appraisal of scientific communication. Since these are new forms of communication for many undergraduate students, instructors report using rubrics to evaluate and provide feedback on the quality of the communication.
d. The final stage of this model relates to the scientific outcomes of the students' work. At this stage, assessment aims to evaluate the quality of the outcomes of these procedures and the level to which the student really understands what they have done. Evaluation here therefore combines the use of data cards, annotation outputs, lab notebooks, oral presentations, conference participation, and the student's reflections on their own work. As reported by faculty, not all procedures are successful and students are not graded negatively for a failed experiment as long as the procedures, including the thinking involved, follows the scientific process. Thus, as reported by faculty, both the instructor and the student often work collaboratively to evaluate how well the student understands the different procedures they are learning to use.

## Model 3: assessing the facilitation of project ownership

The educational practice of a CRE involves a desired transition of the student from being a more passive learner of knowledge to being an active producer of knowledge who is integrated into a larger community of researchers. This transition, in which the student has a sense of ownership over their work and responsibility over their research and learning, is an aim of CRE pedagogy and has important ramifications to being a student researcher (Hanauer et al., 2022). Furthermore, prior research has shown that the development of a sense of project ownership differentiates between an authentic research experience and a more traditional laboratory course. Figure 4 presents the pedagogical and assessment model of fostering project ownership. The model has three stages of development.

a. The first stage of fostering project ownership is developing in students a broad understanding and ability to perform a range of scientific protocols. This is because project ownership requires the belief and the ability to actually do science. It is an issue of self-efficacy and mastery of concepts and skills. As such, the first stage of assessment involves evaluating the degree of mastery a student has over a specific protocol. As opposed to prior models, this is enacted here through formative, informal discussions, which also serves to enhance that mastery.

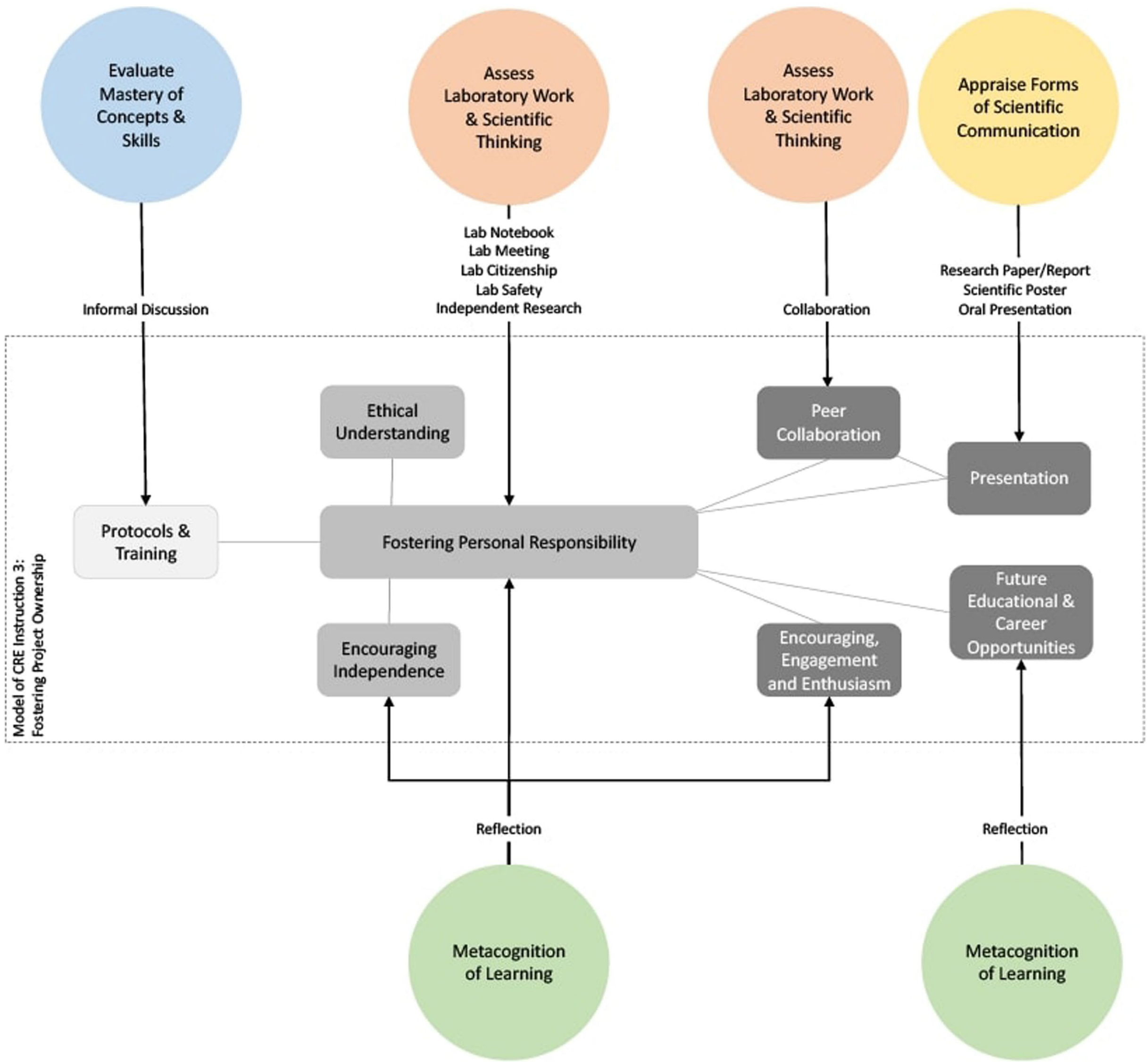


FIGURE 4
Assessing the facilitation of project ownership: this model has three distinct stages. The first stage relates to development of understanding concerning protocol usage. The second stage relates to the fostering of the student's sense of personal responsibility. The third stage involves situating the student within the broader scientific context. The model presents the aims and practices of assessment applied at each of these stages.

b. The second stage of the model aims to develop the student's sense of personal responsibility. Primary to this process is the promotion and encouragement of the student's independence. This can involve both emotional supports, the provision of resources, and the allotment of time for the student to ponder the work that they are doing. As reported by faculty, not every question has to be or can be answered immediately. Allowing a student to think about their work and what *they* think should be done is an important aspect of a CRE education. Accordingly, a central component of the assessment model here is having the student reflect on their work. The task of assessment here thus expands beyond the instructor to student as well.
c. A different aspect of both fostering and assessing responsibility and ownership over one's research involves a series of behaviors related to scientific work. Faculty report assessing lab citizenship, collaboration and lab safety protocols. Being responsible includes behaving in appropriate ways in the laboratory and as such these aspects of the students' work are evaluated. Some faculty also reported that having the student propose projects that extend the ongoing classroom research project allowed them to assess the degree of independence of the student.
d. The final stage of the model involves situating the student-researcher within a broader scientific context. Talking with the student about future careers and educational opportunities, and providing encouragement and enthusiasm for the work the student is doing positions the student at the center of their own development. Project ownership involves pride in the research one is doing and seeing ways in which this work can

be developed beyond the specific course. Once again, reflection plays a central role in assessing and facilitating this, and occurs as an informal and ongoing process.

e. In parallel, the outcomes of the research the student does is reported using established modes of scientific communication. A student is responsible for reporting their work using oral presentations, scientific posters, research papers, and reports. At this point, they will receive feedback on their work in both formal and informal ways. One important aspect of this reporting is the real-world evaluation of their output. Other peer student researchers may respond, in addition to faculty and scientists beyond the classroom. Having ownership over one's research also includes an understanding that the work will be evaluated beyond the classroom grade and that the work itself is part of a far larger community of scientists. In this sense, the evaluation of the scientific output facilitates ownership of the research itself.

## Discussion

The main aim of this paper is to explore how assessment of students engaged in course-based research is implemented and aligned with the educational goals of this form of pedagogy. In terms of constructive alignment, the aims of any assessment program should reflect and support defined instructional objectives. Assessment of scientific inquiry, as is typically implemented in traditional labs, focus on mastery of the components of research (see Wenning, 2007 for an example). The aim of instruction and assessment within a traditional lab is to make sure that a defined procedure has been mastered by the student so that in some future course or scientific project, the student knows how to perform it. In the traditional lab, grading is evidence of qualification for the student's ability to function in a future scientific activity. Failure, if it happens, is indeed failure and a reason for not progressing further.

In contrast, a CRE aims to provide the student with an authentic research experience in which they are contributors of research data that is useful for advancing science. As such, mastery is a necessary but not sufficient aim of assessment. As specified by instructors in this study, mastery of concepts, quantitative thinking and skills is important in order to conduct and understand a scientific process; but this is situated in relation to the actual performance of scientific research (also an aim of assessment), which involves an understanding of how to communicate science and ownership over one's learning and research activity. Thus, from the perspective of what to assess, it is clear that assessment in a CRE needs a broader approach than the assessment program of traditional labs. In this study, four aims of assessment were defined by experienced CRE instructors: (1) Assessing Laboratory Work and Scientific Thinking; (2) Evaluating Mastery of Concepts, Quantitative Thinking and Skills; (3) Appraising Forms of Scientific Communication; and (4) Metacognition of Learning.

The alignment between these assessment aims and the aims of CRE instruction is further explicated here. Across the instructional aims of Facilitating Being a Scientist and Generating Data, Developing Procedural Knowledge, and Fostering Project Ownership, the four aims of assessment were seen to provide ways of collecting useful data that supports the progress of students toward these stated aims of CRE instruction. With regard to how assessment data are collected in a CRE, there are particular relationships between formal and informal assessment and the formative and summative approaches. Summative assessment with formalized tools tended to be at the beginning and end of a research process, in relation to first the development of required mastery of concept and skills and last the evaluation of scientific outputs, which are the products of the research. Mastery can be evaluated using tests and exams, while products can be evaluated using rubrics. In contrast, during the process of conducting the research project, the emphasis is on providing feedback to students to help support the ongoing work. This includes the use of a range of laboratory practices, such as lab notebook documentation and lab meetings. And while assessment data are collected, the response is often informal and formative with the aim of supporting the student to further their research.

Beyond collecting assessment data, there is also a particular way in which assessment, evaluation and grading manifest in a CRE setting. The terms of assessment, evaluation and grading are often used interchangeably. But these terms relate to different concepts. Assessment is primarily a data collection and interpretation task; evaluation is a judgment in relation to the data collected; and grading is a definitive decision expressed as a number or letter as to the final quality of the work of a student. The majority of institutions require grades for a CRE. But not all things that are assessed in a CRE need to be graded. In particular, informal discussion with students of the different aspects of the scientific tasks students are performing allows the instructor to provide supportive feedback that facilitates the scientific inquiry. This informal, formative assessment does not require a grade directly. At the same time, there is a role for assessing and grading the underpinning knowledge, behaviors (such as lab citizenship, attendance, participation, collaboration, and lab safety), and scientific outputs of the students. Thus, there is a two-tiered assessment and grading process in which, during the process of scientific inquiry, which is the majority of the course time, assessment data are collected but not graded; however, the knowledge, skills, behaviors, and outcomes are graded. Since the aim of the whole course is to give the student the experience of being a researcher and to produce scientific data, providing facilitative feedback based on assessment during the research process helps the student to complete the tasks in a meaningful way. The grading of the underpinning knowledge, skills, and behaviors also facilitates the work that is conducted in laboratory. Without appropriate mastery and behavior, the lab research will not be possible. Thus, once again, the form of assessment supports the progress of authentic research. As presented in this study, the way to grade a CRE is to differentiate the framing of the research that is conducted from the process of doing the research; provide extensive formative assessment in an informal manner throughout the research process; grade the underpinning components of knowledge, skill, and behavior; and provide a final grade which weights the quality of the work and the output that is produced. The aim should be for every student to be successful in the research process and assessment should facilitate this work.

The assessment and grading practices presented here are clearly facilitative of student learning. First, knowledge, skills, and behaviors are measured because they are foundational for students to productively engage in their research. Second, a large part of the assessment work is directly aimed at providing feedback without penalizing a student through grade assignment. There is extensive informal formative assessment that can be seen as a departure from assessment in more traditional labs and which approximates the type of facilitation that characterize mentor-mentee relationships in authentic research settings (e.g., in individual undergraduate research experiences, postbaccalaureate research opportunities, or during postgraduate research). This mentor-mentee relationship can build trust and counter stereotype threat to enhance persistence and learning. Additionally, an assessment program with extensive informal formative assessments leaves fewer instances when a student might be penalized by grading and suffer the negative psychological effects associated with lower grading. Third, the components of CRE assessment address a broad range of skills, beyond just mastery of procedures that a student needs as a scientist and a learner. In particular, included within the aims of CRE assessment are scientific communication and metacognition. Scientific communication is an important component of being a researcher, while metacognition not only provides information that can be used to evaluate where a student is and how they are thinking about their work, but also positions the student as an evaluator of their own work. In this case, the task of assessment itself directs the students toward better learning and might explain why CREs improve student learning despite the CRE content not always being directly aligned with lecture content (in comparison to traditional lab). We hypothesize that these various aspects of CRE assessment contribute to the positive outcomes observed for students across many demographics and when compared to the traditional lab.

As presented in the introduction, a CRE poses quite specific challenges in terms of assessment and grading. A primary concern relates to the need to maintain a professional shared research project with contributions from instructor and student, while still assessing and grading a student. As presented here, this delicate balancing act is facilitated by using assessment and grading thoughtfully and in a coordinated manner. If the instructor is providing extensive feedback that supports the work of the student and grades the aspects of science that are necessary for the student to succeed, the relationship with the student is different from a relationship in which the teacher is just grading a student. The assessment models presented here provide a framework to facilitate the aims of a CRE without undercutting the broader aims of promoting student learning and persistence in science, and can serve to inform assessment and grading practices in STEM, more generally.

## Limitations

The data and analyses presented in this study emerged from a collective process with a large number of faculty who all implement CREs through the Science Education Alliance (SEA) program by HHMI. Organized as an inclusive Research and Education Community (iREC), faculty in the SEA program are supported by centralized programming to lead the instruction of research projects with a shared research agenda (Hanauer et al., 2017). This does have some ramifications that limit the generalizability of the current results. First, CREs with different research agendas and that require different procedures may change the ratios of formal and informal assessment and what is considered important for grading. Second, while the instructors do work at a wide range of institutions, they also work together in SEA. There is extensive interaction between instructors facilitated by yearly in-person faculty meetings, monthly science and education seminars, and on-line shared resources. This familiarity, interaction and shared course components can lead to a degree of homogeneity in relation to how procedures such as assessment and grading are conducted. As the SEA community facilitated the current data collection and analysis process, it can limit results by not including a much broader set of underlying CRE educational and scientific designs.

## Conclusion

Course-based research experiences are increasingly implemented at institutions of higher learning because they offer a strategy to scale-up opportunities for students to engage in authentic research, which is strongly correlated with an increased persistence in science for a wide range of student populations (Russell et al., 2007; Jordan et al., 2014; Hanauer et al., 2017; Hernandez et al., 2018). However, given that CREs situate the research opportunity within the context of a course, it is critically important that the involvement of course grading does not negatively influence students' belief in their abilities and willingness to persist in STEM (Hatfield et al., 2022). As seen in the reviews of the multiple instruments developed for the assessment of students in a CRE, the past tendency has been to conceptualize the goals of CRE as a set of skills, competencies, dispositions and abilities to be gained by students for their future engagement in research (Shortlidge and Brownell, 2016; Zelaya et al., 2022). The assessment of such externalized goals instead of the actual science and scientific process that is at the core of the CRE can lessen the value of the research students are engaged in and contradict their self-perception as researchers.

In contrast, the study presented here models how faculty actively teaching in a large CRE program have integrated assessment into their CRE pedagogy in a way that supports the actual research that is being conducted. In this way, assessment and grading are directly tied to the intended value and aim of a CRE in providing students with an opportunity to engage in research authentically. This is particularly critical because students' sense of being a scientist is foundational to long-term persistence in the sciences and inappropriate assessment and grading practices could interfere with the positive social and educational values embedded in a CRE (Hanauer et al., 2017). The models of assessment presented here describe how assessment and grading can be conceptualized and implemented in a way that maintains the student's authentic sense of being a researcher. The approach to assessment described in this paper, which emerged from an extensive interaction with a large community of faculty who actively teach a CRE, describes ways in which assessment can support the educational and social agenda of a CRE. We hope that this study will encourage other researchers working a wider range of CREs to study their own assessment and grading objectives and practices and consider the ways in which assessment can facilitate and not hinder the student's research experience.

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## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

## Ethics statement

The studies involving humans were approved by Indiana University of Pennsylvania, IRB #21-214. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

DHa: Conceptualization, Formal analysis, Investigation, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. TZ: Formal analysis, Writing – review & editing. MGr: Conceptualization, Writing – review & editing. SA: Validation, Writing – review & editing. YA-S: Validation, Writing – review & editing. RA: Validation, Writing – review & editing. MAn: Validation, Writing – review & editing. MAy: Validation, Writing – review & editing. ME: Validation, Writing – review & editing. CBa: Validation, Writing – review & editing. TB: Validation, Writing – review & editing. MBe: Validation, Writing – review & editing. EB: Validation, Writing – review & editing. AB: Validation, Writing – review & editing. RB: Validation, Writing – review & editing. DB: Validation, Writing – review & editing. LB: Validation, Writing – review & editing. VB-K: Validation, Writing – review & editing. MBu: Validation, Writing – review & editing. SB: Validation, Writing – review & editing. KB: Validation, Writing – review & editing. CBy: Validation, Writing – review & editing. SCa: Validation, Writing – review & editing. CC: Validation, Writing – review & editing. RC: Validation, Writing – review & editing. H-MC: Validation, Writing – review & editing. KCl: Validation, Writing – review & editing. SCol: Validation, Writing – review & editing. DPa: Validation, Writing – review & editing. SCon: Validation, Writing – review & editing. BrC: Validation, Writing – review & editing. PC: Validation, Writing – review & editing. BeC: Validation, Writing – review & editing. JC-E: Validation, Writing – review & editing. KCr: Validation, Writing – review & editing. TD'E: Validation, Writing – review & editing. MD: Validation, Writing – review & editing. LDe: Validation, Writing – review & editing. LDi: Validation, Writing – review & editing. ID: Validation, Writing – review & editing. NE: Validation, Writing – review & editing. 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review & editing. DJ-S: Validation, Writing – review & editing. GH: Project administration, Supervision, Validation, Writing – review & editing. DA: Funding acquisition, Project administration, Supervision, Validation, Writing – review & editing. VS: Funding acquisition, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

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# Unveiling interdisciplinary horizons: students' experiences in a first-year calculus course

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In the realm of higher education, the pursuit of interdisciplinarity aims to foster the exchange and integration of fragmented knowledge, yielding transformative outcomes. Employing a phenomenological method, this study delves into the interdisciplinary experience of twelve students from a first-year undergraduate calculus class. Through the analysis of written questionnaires, focus group sessions, and supplementary qualitative data, a comprehensive understanding of students' interdisciplinary encounters is unveiled and organized into three main categories: what students think about interdisciplinarity, how they act when being involved in integrations and what external factors are involved in shaping their experience. This paper presents emergent experiential themes, shedding light on both individual and collective experiences, as students navigate and enrich their calculus learning through interdisciplinary connections.

KEYWORDS

**interdisciplinary education, students' perspectives, phenomenological analysis, interdisciplinary experience, calculus, engineering students, higher education, educational innovation**

## 1 Introduction

Interdisciplinary educational perspectives veil knowledge that once was fragmented and atomized within disciplinary and subdisciplinary units. However, these perspectives aim to integrate and transcend their own boundaries. The holistic attributes of interdisciplinary education enhance students' learning experiences and inspire innovative educational strategies (Broggy et al., 2017). As the world grapples with increasing complexities and recognizes the necessity of addressing intricate issues (Davies et al., 2010), the importance of interdisciplinary approaches becomes evident. This realization acknowledges the need to "productively and potently address problems defined by interdependencies across systems" (Tarrant and Thiele, 2017, p. 356), driving the search for linkages beyond disciplinary borders and transversal skills (Carter et al., 2021).

Interdisciplinarity is often referred to as a pedagogical process that identifies common learning and concepts across multiple subjects to address a central theme. It aims to unravel how subjects relate to each other and the overarching theme (Broggy et al., 2017, p. 81). Moreover, it aligns with epistemological definitions that emphasize the integration of "information, methodologies, techniques, skill sets, or theoretical perspectives from two or more disciplines" (Tarrant and Thiele, 2017, p. 355). These notions underscore the significance of cultivating competences for interdisciplinarity, including synthesizing knowledge, fostering complex critical thinking skills, nurturing effective communication abilities, and adopting attitudes conducive to exchanging and transcending disciplinary knowledge in pursuit of integration (Parker, 2010; Madina et al., 2023). These aptitudes are widely regarded as beneficial learning outcomes of interdisciplinary higher education (Spelt et al., 2009, p. 366).

Particularly, interdisciplinary education in mathematics has emerged as a focal research area within mathematics education, particularly concerning teaching and learning phenomena within the STEM education agenda (Williams et al., 2016). However, a notable challenge exists: a "lack of clarity about what mathematics-science integration actually looks like in practice" (Broggy et al., 2017, p. 85), particularly in instructional scenarios where mathematics is not the primary source of disciplinary integration, but rather is perceived as a tool "in the service of science learning." This gap highlights the need for empirical evidence to substantiate learning gains resulting from integration approaches and to comprehend the daily classroom experiences associated with them.

Empirical studies addressing the interdisciplinary education of mathematics focus on teachers' experiences. For instance, they explore the implementation of such approaches in elementary and middle school STEM programs, emphasizing the connections between mathematics and technology (Jehlička and Rejsek, 2018). Similarly, research delves into the experiences of high school vocational teachers engaged in interdisciplinary team-teaching (Kodkanon et al., 2018) and the challenges faced by high school teachers in making curricular trade-offs (Weinberg and McMeeking, 2017). Furthermore, studies investigate teachers' perceptions of STEM pedagogy in higher education (El-Deghaidy et al., 2017; Vink et al., 2017; Dare et al., 2018; Carter et al., 2021), examine the effects of collaborative interdisciplinary modules on students' behavior, attitudes, and motivation (Kelly et al., 2020), and identify systematic and practical concerns in middle schools (Samson, 2014) as well as higher education institutions (Klaassen, 2018; Hart, 2019; Pascale et al., 2021). These studies collectively underscore that interdisciplinary education introduces substantial challenges, not solely concerning teaching and learning dynamics, but also encompassing institutional structures and students' perceptions and appreciation of interdisciplinarity. It is important to note that multidisciplinarity, interdisciplinarity, and transdisciplinarity are all integrative educational approaches and are part of curriculum integration (Beane, 1997; Fraser, 2013), nevertheless their differences rely on the mesh level of connections, focuses, aims, learning outcomes and cooperations.

Epistemological and pedagogical concerns, particularly within higher education contexts, draw attention to issues such as paradigmatic incompatibilities, language barriers, the dominance of ideas, and the need for a deeper understanding of content (Davies et al., 2010). A sufficient grasp of disciplinary knowledge is deemed essential to help students surmount these challenges, enabling them to recognize the necessity for gradual development of interdisciplinary skills and to identify appropriate scenarios for applying interdisciplinary perspectives:

> Within interdisciplinary classrooms often students are presented with contrary disciplinary perspectives that may confuse or frustrate them and unless they have developed a clear understanding of the knowledge and conceptions of the nature of interdisciplinary teaching they will be unable to make sense of the information. (Broggy et al., 2017, p. 82).

Once again, the pivotal concern "of how best to incorporate it (interdisciplinarity) into students' learning experiences is a key consideration in a changing global context" (Davies et al., 2010, p. 19) comes to the forefront. Nonetheless, the experiences and challenges encountered by students within interdisciplinary learning processes remain understudied and insufficiently understood.

Several authors have explored the student experience within pedagogical projects focused on integrating knowledge from various disciplines (Jennett et al., 2017; Self and Baek, 2017; Hall et al., 2018; Munge et al., 2018; Hero and Lindfors, 2019; Power and Handley, 2019). For example, Hall et al. (2018) present findings from a questionnaire surveying the experiences and perceptions of undergraduate students from different higher education institutions that shared exposure to multidisciplinary modules within geography programs. Similarly, Hero and Lindfors (2019) employed a phenomenographic approach to explore how undergraduate students engage with learning in multidisciplinary teams. Jennett et al. (2017) examined the experiences of students participating in a science gamer lab summer school, where interdisciplinary teamwork was an integral component. Additionally, Munge et al. (2018) conducted a literature review on outdoor fieldwork as an experiential learning method in higher education, focusing on the multidisciplinary aspects of fieldwork in various fields. Power and Handley (2019) surveyed the obstacles faced by higher education institutions when integrating interdisciplinarity into student learning experiences, along with identifying key facilitators and potential solutions to enhance the successful integration of interdisciplinary collaboration into the student learning journey.

This background underscores the relevance of employing qualitative inquiry methods to unravel the experiential essence and significance of interdisciplinarity from the student perspective. This paper presents an analysis based on Moustakas (1994) phenomenological method, aimed at uncovering the interdisciplinary experience of twelve first-year undergraduate students enrolled in a calculus course. Through questionnaires, focus group interactions, and reflective journaling, the study seeks to address the following question: How do these students perceive and navigate the presence of interdisciplinarity within a first-year mathematics class?

## 2 Methodology

In this section, we present the research designed followed by the authors reflection as this project advanced as well as her final reflection looking back. Followed by the participants, data collection, and data analysis.

### 2.1 Research design

The inherent beauty of the phenomenology philosophy and their derived methods lies in its meticulous capacity to distill and comprehend the intricate diversity of heterogeneous experiences surrounding a phenomenon, ultimately reaching its most refined descriptive and interpretative state. This approach entails a profoundly reflective research process that facilitates a comprehensive understanding of individual experiences in harmony with the broader array of collective experiences. Thus, the essence of participants' interdisciplinary encounters is unveiled in a holistic and untainted manner, offering substantial evidence of interdisciplinary practices in the teaching of integrated college calculus knowledge.

Inspired by the methodological framework proposed by Dare et al. (2018) for comprehending teachers' experiences in implementing interdisciplinary curricular units, this study uses a case study approach for data collection and a phenomenology framework to analyze the data. The selection of a case study methodology stems from its capacity to enhance the descriptions and interpretations of participants' experiences, yielding a diverse range of evidence to construct a 'deep description and analysis of a case' (Creswell and Creswell, 2018, p. 104), which, in the context of this study, pertains to the delineation of the essence of the phenomenon of interest.

Likewise, the philosophy of phenomenology has been adopted to delve into the 'essence or basic structure of the experience' (Merriam, 1998, p. 16), specifically interdisciplinarity. This entails employing firsthand data that captures participants' experiences within a specific context – the setting being a first-year college calculus class. This approach engages in a fundamentally philosophical exploration to perceive interdisciplinarity as a phenomenon that can 'distill individual experiences into a description of a universal essence' (Creswell and Creswell, 2018, p. 75). According to Merriam (1998), a case study methodology can seamlessly merge with other forms of qualitative research due to its inherent capacity for providing comprehensive descriptions. This methodological fusion underscores the central inquiry: What constitutes participants' interdisciplinary experiences and how do they perceive them?

## 2.2 Own interdisciplinary experience

In conjunction with the "phenomenological epochè" (Husserl, 1977), the pursuit of a self-conscious state is paramount, as described by the author who articulates it as "apprehending myself purely: as Ego with my own pure conscious life, through which the entire Objective world exists and is precisely as it is for me." (p. 21). This endeavor prompts a responsibility for researchers to introspect on their own thoughts, emotions, and experiences concerning the research theme. Sharing these reflections with the readers of this paper bears great significance as it elucidates the origins of the researcher's interest in exploring this phenomenon through the lens of the phenomenological approach.

The deliberate intent behind conveying to students the sense of multi-competence, adept management of skills, and the cultivation of holistic life perspectives – both personally and professionally – fosters a personal optimism towards interdisciplinarity, a sentiment that is handled delicately in this study. The unfolding events within the analyzed class period also called for introspection. For instance, the process of devising interdisciplinary activities for the class evoked both delight and stress simultaneously, stemming from the aspiration to maintain the connections as pure and useful as possible. In this course, we explored the integration of novel learning activities and innovative pedagogical approaches to enhance interdisciplinary educational outcomes. Immersive learning experiences were promoted, such as interactive simulations available at the University of Colorado's PhET[1] and augmented reality experimentation with the use of open-source software Tracker.[2] Additionally, we purposely aimed to develop physics and mathematical modelling, critical thinking, and problem-solving competences, therefore most learning activities sought to start from a phenomenon related to the students' daily lives or relatable situations that could deeply contextualize learning. Perceptions of these activities were diligently documented within a reflective journal maintained throughout the 4 months duration of the class. Reflections proved instrumental in the subsequent analysis and delineation of the essence of students' interdisciplinary experience.

## 2.3 Participants

As advocated by Creswell and Creswell (2018), exploring a phenomenon within a cohort of individuals who have personally encountered it suggests the inclusion of a diverse group of 10 to 15 individuals. This rationale substantiates the unit of analysis for this study – a cohort of 12 students who collectively share an interdisciplinary experience within a first-year mathematics class offered by a university situated in northern Mexico. The course is conducted in English, catering to students enrolled in honors academic programs. The selection of the participant pool adheres to a "convenience" (Merriam, 1998, p. 63) sampling approach, chosen due to their shared involvement in the phenomenon under study and their varied academic program backgrounds. Furthermore, the selection encompasses students enrolled in a course where the authors have actively engaged in both the design of learning sessions and their execution.

An additional motivation for selecting this calculus group pertains to the resistance against traditional and mechanistic approaches to teaching calculus, observed among those who facilitated the learning process for the group. These facilitators champion student-centered methodologies and employ experimental resources and technology to enhance the learning journey. The instructors of the examined course meticulously crafted activities aimed at fostering the cultivation of interdisciplinary competencies, deliberately opposing pedagogical methods that might be incongruent with the nurturing of interdisciplinary experiences.

## 2.4 Data collection

Two principal techniques were employed to comprehensively capture and document participants' interdisciplinary experiences: a written open-questionnaire and a focus group protocol. For the written open questionnaire, the foundational inquiries proposed by Moustakas (1994) served as the cornerstone for constructing the specific questions related to the experience of interdisciplinarity. Collaborating with the teacher team, a questionnaire comprising four open-ended questions was meticulously formulated and administered during the initial month of the course. The questions encompassed: (1) In your mathematics class, what instances of ideas from other fields do you discern? (2) How do you recognize the application of mathematics within the context of your chosen field of study? (3) What factors shape your perception of mathematics in your everyday life? (4) Which real-life scenarios have facilitated your comprehension of the concepts covered in your mathematics class?

Regarding the focus group protocol, the two fundamental questions aimed to unravel participants' experience were posed to the

1 https://phet.colorado.edu/en/
2 https://physlets.org/tracker/

participants, who were already familiar with the topic and theme. These questions were presented verbatim and left open to the participants' interpretation.

In conjunction with the primary data collection techniques aforementioned, a quantitative instrument for gauging interdisciplinary perception (Hernandez-Armenta and Dominguez, 2019) was administered. Additionally, meticulous records were maintained for each interdisciplinary activity conducted over the 4 months duration of the course. Researchers' participant observations were recorded in a reflective journal along with detailed field notes. An online collaborative journal for students was maintained, and visual documentation, such as photographs of various class activities, was also amassed. Ethical considerations were diligently upheld throughout the research process (Creswell and Creswell, 2018, p. 54), encompassing the completion of consent forms by all study participants and ensuring the safeguarding of their anonymity.

## 2.5 Data analysis

The research design adheres to the methodological framework proposed for phenomenological inquiries by Creswell and Creswell (2018, pp. 78–80), encompassing the following systematic steps:

1. *Determination of phenomenological perspective*. The initial step involved ascertaining the appropriateness of a phenomenological perspective to explore the research problem.
2. *Phenomenon identification and description*. Subsequently, the phenomenon of interest was meticulously identified and described in a comprehensive manner.
3. *Clarification of philosophical assumptions*. The distinct philosophical assumptions underpinning the phenomenological approach were carefully delineated and elucidated.
4. *Data collection from participants*. Data were gathered from participants who collectively shared first-hand experiences of the phenomenon.
5. *Generation of meaningful analysis themes*. By delving into the gathered data, key analysis themes were derived, encapsulating the core essence of the participants' experiences.
6. *Development of textual and structural descriptions*. Subsequent to establishing the analysis themes, the process involved constructing rich textual and structural descriptions that conveyed the nuanced layers of the phenomenon's essence.
7. *Presentation of the phenomenon's essence*. The culmination of the analysis process entailed the creation of composite descriptions that succinctly captured the essence of the phenomenon, resulting in an integrated and profound understanding.
8. *Presentation of findings*. The ultimate goal encompassed presenting the in-depth comprehension of the phenomenon's essence in written form, thus conveying a coherent and illuminating narrative.

For the progression of steps 5 through 8, the framework formulated by Moustakas (1994) (depicted in Figure 1) has been embraced, providing a structured methodology for categorization and description development, thereby fostering a comprehensive and insightful understanding of the phenomenon's essence.

# 3 Findings

In this section we present and elaborate on the discussion of the results.

## 3.1 Participants' experiences

To facilitate the analysis process, transcriptions of the video and audio recordings from the conducted focus groups were meticulously transcribed. Subsequently, the verbatim expressions that held direct relevance, extracted from these transcriptions, were organized. The qualitative data analysis software was instrumental in accommodating the flexibility of multiple data categorizations. A comprehensive node database was constructed, bolstered by pertinent expressions derived from the written questionnaire administered to the participants. The complete set of expressions (totaling 126) was utilized to facilitate its categorization into constituent units (23), as illustrated in Figure 2. Within this intricate framework, a total of nine invariant units emerged within the theme of "What I feel," five for the "What I do" aspect, and an additional nine for the "What influences my experience" topic. These units, extracted from the expressions shared by all twelve participants, collectively contributed to a nuanced and comprehensive exploration of their interdisciplinary experiences.

From these invariant constitutive units, textural descriptions were meticulously crafted to encapsulate the essence of what participants were experiencing. Concurrently, structural descriptions were meticulously developed to delve into the influences and modalities through which these experiences were navigated by the participants (as illustrated in Table 1).

Throughout the focus group sessions, an in-depth exploration of participants' perspectives and opinions concerning the attitudinal dimensions of their interdisciplinary experiences was undertaken. The discussions were guided by two central questions: "What attitudes, in your view, are closely linked to interdisciplinarity?" and "Which attitudes best encapsulate your personal mindset during mathematics class in the context of interdisciplinarity?" To visually depict the recurring responses from participants, a word cloud was generated (refer to Figures 3A,B). This graphical representation serves to provide a clear visualization of the prevalent terms shared by the participants.

Regarding attitudes towards interdisciplinarity, participants collectively endorsed the significance of maintaining an open-minded disposition, coupled with a proclivity for thinking innovatively, fostering creativity, and nurturing empathy – all of which were deemed crucial for fostering interdisciplinary practices within the classroom setting. When delving into their own personal attitudes towards interdisciplinarity, students further highlighted qualities such as curiosity, receptiveness, and respect for diverse perspectives. Notably, participants also candidly acknowledged the presence of counterproductive attitudes, including idleness and demotivation, which emerged as the most prevalent antagonistic outlooks.

# 4 Discussion

## 4.1 Towards the essence, invariant units, textural, and structural tangle

As the tapestry of textural and structural descriptions, found on Table 2, weaves together the once fragmented conversations, a holistic

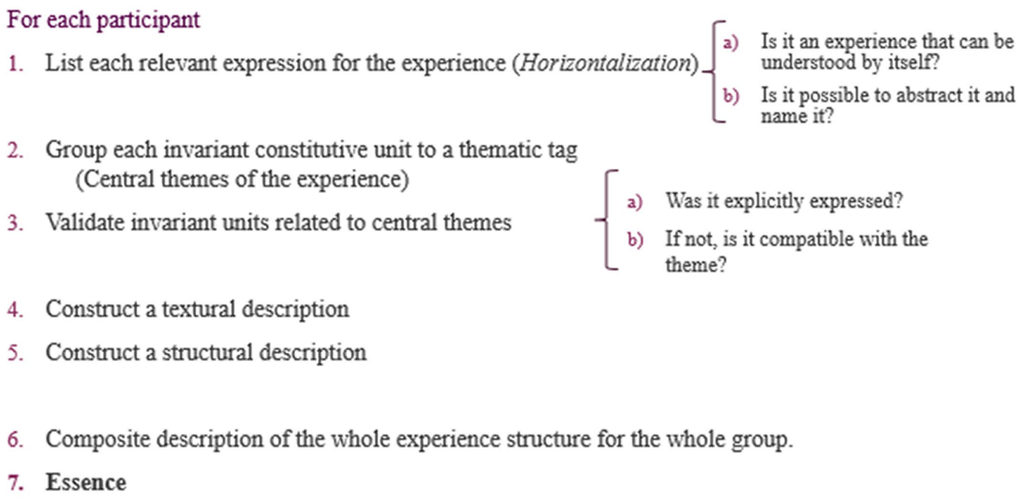


FIGURE 1
Moustakas' (1994) modification of Van Kaam phenomenological analysis method.

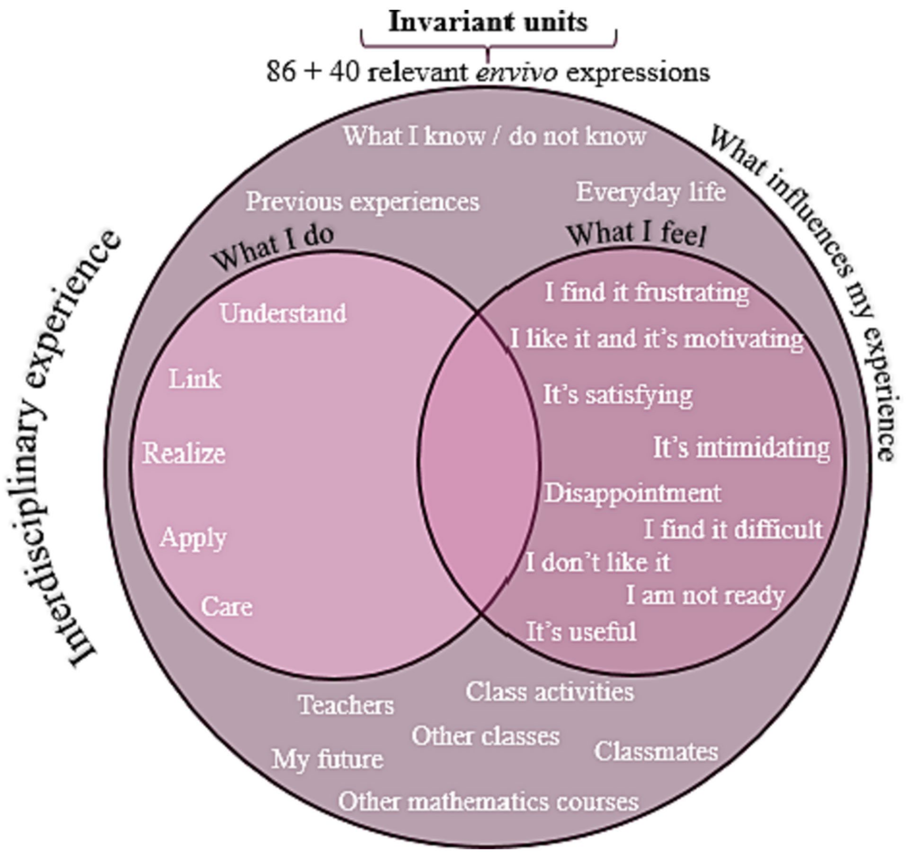


FIGURE 2
Invariant units for interdisciplinary experience of the Mathematics I group.

understanding of each participant's experience comes into focus. An intermediary stride in advancing toward the construction of the 'composite description' of the phenomenon (Creswell and Creswell, 2018, p. 201) involves interlacing the invariant units, textural nuances, and structural intricacies.

Within the process of making textural and structural descriptions, themes begin to coalesce, gradually illuminating pertinent facets that contribute to the overarching essence of the interdisciplinary experience. Other data collected items lend their weight to this phase, offering triangulation and reinforcement to

TABLE 1 Invariant units (What I feel, What I do, and Influences).

| ID | What I feel | What I do | Influences |
|---|---|---|---|
| P1 | -I find it frustrating<br>-It's satisfying<br>-I like it and it motivates me<br>-It is intimidating | -Link<br>-Understand<br>-Realize | -What I do not know<br>-Classmates<br>-Previous experiences |
| P2 | -I find it difficult<br>-I like it and it motivates me<br>-Disappointed | -Link<br>-Apply<br>-Realize | -What I do not know<br>-My future<br>-Previous experiences |
| P3 | -I find it difficult<br>-It's satisfying<br>-I like it and it motivates me<br>-It is intimidating | -Link<br>-Apply<br>-Realize | -What I do not know<br>-What I know<br>-Previous experiences |
| P4 | -I find it difficult<br>-I do not like it<br>-I am not ready | -Apply<br>-Realize | -What I do not know<br>-Other mathematics courses<br>-Class activities<br>-Previous experiences |
| P5 | -I find it difficult<br>-It's satisfying<br>-I like it and it motivates me<br>-It is intimidating | -Link<br>-Understand<br>-Care | -What I do not know<br>-Classmates<br>-Previous experiences |
| P6 | -It's satisfying<br>-I like it and it motivates me | -Link<br>-Understand<br>-Apply | -What I know |
| P7 | -It's useful<br>-I like it and it motivates me | -Link<br>-Understand<br>-Apply | -What I know |
| P8 | -It's useful<br>-I like it and it motivates me | -Link<br>-Understand<br>-Apply | -Class activities<br>-Classmates |
| P9 | -It's satisfying<br>-I like it and it motivates me<br>-It's useful | -Link<br>-Understand<br>-Apply | -What I know<br>-Previous experiences<br>-Everyday life<br>-Other courses<br>-Classmates<br>-Teachers |
| P10 | -It's satisfying<br>-I find it difficult<br>-It's useful | -Link<br>-Realize | -What I know<br>-Previous experiences |
| P11 | -It's useful | -Apply | -What I know<br>-Previous experiences |
| P12 | -I find it difficult | -Understands<br>-Realize | -Everyday life<br>-Class activities |

underscore the relevance of these aspects in shaping the final composite framework.

## 4.2 Challenges in linking, understanding, and applying

A subset of participants – namely, Participants 1, 2, 4, and 12 – voiced a sense of interdisciplinarity as a challenge, articulating emotions ("What I feel" invariant units) such as frustration, intimidation, disappointment, difficulty, and even aversion. These emotions reverberate to impact their comprehension of class activities, application of mathematical concepts, and connection with other fields of knowledge. This sentiment is particularly prevalent among participants who grapple with two primary influences: gaps in their existing understanding and a lack of previous exposure to linking mathematics across disciplines.

For Participants 1 and 2, the inhibition stems from a perceived lack of foundational comprehension of mathematical methods, leading to a hesitance in initiating cross-disciplinary connections. As Participant 1 candidly expressed, "sometimes I'm like "damn, I do not know"." Participant 2 similarly shared, "since there are things I do not know, it influences my experience because I lack the foundation to make connections." This resonates with participants who find solace in sticking to familiar concepts, perceiving a lack of readiness to venture into interdisciplinary explorations.

Moreover, certain participants, such as 10, 11, and 9, have never previously conceived that mathematics could intertwine with other disciplines. Negative prior experiences with math classes have left participants 10 and 11 apprehensive, preventing them from conceiving any form of connection between their chosen career paths and mathematics. On the other hand, Participant 9, driven by a history of never making such links, finds motivation to persist in their attempts.

Participants 4, 10, and 12 encountered difficulties in the application of mathematical concepts from their class to other concurrent courses. These observations parallel Davies et al., 2010 viewpoint on the influence of past disciplinary knowledge on perplexing and frustrating experiences, disrupting interdisciplinary encounters. Additionally, the insights of Hall et al. (2018) on students' familiarity with discussed concepts and the confidence emanating from shared professional language contribute to shaping participants' varied experiences. This phenomenon may also impact student engagement and their perception of assessments, contributing to the intricacies of interdisciplinary exercises (Self and Baek, 2017).

## 4.3 Utilitarian value and practical application

For a substantial portion of the participants (P5, P6, P7, P8, P9, P11), their accounts of the interdisciplinary experience revolve around a profound realization, an emotional resonance, and cognitive connections that underscore the significance of mathematics as a practical tool extending beyond their class. These participants contemplate the potential applications of their mathematical knowledge across various subjects and projects, both within their academic journeys and their envisioned professional trajectories. A noteworthy observation is that these sentiments and actions are deeply rooted in the bedrock of existing knowledge – a secure foundation upon which new interconnections can be forged. As eloquently stated by Participant 8, "what you already knew, before what you are learning because you can then relate that, if you do not know it you obviously cannot relate it." Participant 9 echoes this sentiment, acknowledging that expanding knowledge allows for more intricate linkages with the familiar, stating, "if you have more extensive knowledge, I could not relate things with climate change because I did not know much and now that I know something, I can say that 'ah, it is similar to that.'"


FIGURE 3
**(A)** (left) and **(B)** (right). Word clouds from answers provided by participants regarding attitudinal aspects for interdisciplinarity **(A)** and for their personal attitudes about interdisciplinarity in Mathematics I class **(B)**.

For Participants 2, 5, and 6, the intertwined nature and real-world applicability of mathematical knowledge within their future professions and undertakings take precedence. They emphasize the value of these associations forged within the classroom, a testament to the importance of interrelating disciplines for personal and professional growth. Participant 6 eloquently encapsulates this sentiment, stating, "you do not ignore it, like, okay I already passed math I, check." Moreover, this interconnectedness also serves as a potent wellspring of motivation. As Participant 2 puts it, "for certain projects that I want to do, now I have more knowledge of some things, as they relate to what we are studying, so I always keep that in mind, so I can achieve the things that I do."

These insights align with Hero and Lindfors's (2019) observations concerning students' independent work and becoming "aware of" the usefulness of interdisciplinarity, as they active build team competences, agency of collaboration through communication and the competence of being aware of their own and collective learning and skills development. The recognition of the connection between interdisciplinary mathematical experiences and future endeavors is underscored by the articulation and value of interdisciplinary proficiency within professional work environments (Power and Handley, 2019). Additionally, the integration of theory and practice inherent in interdisciplinary approaches can cultivate heightened motivation, offering a clearer understanding of the purpose, value, and rationale behind learning activities. This integration encourages students to adopt an integrative approach to learning while envisioning themselves within their future roles (Munge et al., 2018).

## 4.4 Appreciation for interconnectedness

Several participants, including Participants 2, 3, 5, 7, 8, 9, and 10, enthusiastically express their fondness for the intricacies woven between mathematics and diverse subject areas. Their responses emphasized the realization that everything is connected, that mathematics can be applied in ways they have not imagined before. This newfound awareness fuels an elevated understanding of concepts, creating a web of understanding through the linking of disparate ideas. Moreover, this process triggers a sense of motivation, compelling participants to delve into the intricacies of natural phenomena with a broadened perspective. In the classroom, students were motivated to use technology to make connections and go deeper in their discussion (Figure 4). Participant 7 beautifully captures this sentiment "I really like how it is related to the class because mathematics opens up a landscape for all of us to be able to understand the same phenomenon and in some way describe it and predict what could happen."

Intentionally, class activities were designed to empower students to construct their own knowledge, fostering the discovery and decision-making process in shaping their personal understanding. Participant 9 articulates this sentiment "I really like that in class we do not just cover a topic and take it for granted because we just learned what to do, but we understand the uses so we can make links (…) at some point, we can relate it (what he learned) when we really need it."

Notably, participants 8 and 12 express contentment with the chosen thematic activities, embracing the diverse range that spans biology, natural phenomena, growth, cost, and economics. Their enthusiasm for these diverse themes echoes their embrace of interdisciplinary content and its applications in multiple contexts.

Remarkably, the transition from initial frustration to profound enjoyment is echoed by Participants 1 and 12, who highlight a remarkable shift in their attitudes toward interdisciplinary experiences. Initially, class felt daunting and perplexing, but the transformative power of interdisciplinary learning soon imbued it with a sense of enjoyment and illumination. As Participant 1 candidly notes, "before, class seemed frustrating, now I'm like "I love math class!", it's awesome, I get how the world works."

These nuanced responses resonate with the findings of Hero and Lindfors (2019), who spotlight the duality of teamwork experiences. While some students relish the opportunity to reshape their professional identities and embrace adaptability, others grapple with self-esteem and self-management challenges, along with the intricacies of collaborative problem-solving. Much like their study, our research underscores the broader benefits of interdisciplinary engagement, allowing participants to recognize each other's competencies, experiences, strengths, and areas for growth, while simultaneously fostering a deepened appreciation for their own learning journey.

TABLE 2 Textural and structural descriptions per participant (reduced table).

| ID | Textural description *What is being experienced?* | Structural description *How is the experience lived and what influences it?* | Attitudes towards interdisciplinarity |
|---|---|---|---|
| P1 | Realized mathematics are difficult to link.<br>Transitions from frustration to enjoyment.<br>Transitions from not understanding to start linking. | Influenced by what she does not know and by classmates' competences.<br>Influenced by others' field of expertise.<br>Influenced by previous academic experiences. | Negativity, enthusiasm, curiosity. |
| P2 | Finds it difficult to make connections.<br>Likes mathematics and that is a motivation to link and understand.<br>Realizing that mathematics was going to be connected was disappointing. | Influenced by lack of knowledge.<br>Motivated by future projects. | Connections, many ways to do things, open-mindedness, blocking. |
| P3 | Realizes that everything is connected and likes it.<br>Applies mathematical knowledge and relates it with physics. | Influenced by previous knowledge.<br>Bringing memories to class. | Resistance and openness to know. |
| P4 | Finds it very difficult.<br>Likes traditional mathematics, not ready for connections.<br>Understands the importance, but it is not comfortable.<br>Thinks mathematics is a world apart. | Comparing with other math classes.<br>Influenced by class activities. | Optimism, idleness. |
| P5 | Understands math in a better way.<br>Cares about real life applications of mathematics.<br>Spontaneously links math knowledge with everyday life. | Having positive previous academic experiences with interdisciplinarity.<br>Influenced by past and present teachers. | Empathy, being open to knowledge, accepting help from others and questioning my results and others'. |
| P6 | Gets a better understanding of math relating it with physics.<br>Finds mathematics useful to think. | Influenced by his career choice. | Curiosity, reasoning and conformism. |
| P7 | Understands mathematics as a tool.<br>Likes relating mathematics. | Influenced by previous knowledge. | Curiosity, finding explanations, being an observer, being other points of view, creativity. |
| P8 | Likes mathematics.<br>Applies mathematics in many useful contexts. | Influenced by class activities.<br>Influenced by classmates and teamwork.<br>Influenced by what he already knows. | Lack of motivation and observer attitude. |
| P9 | Makes useful connections.<br>Realizes that math is everywhere, and that interests him. | Lacking previous experience relating mathematics with other fields.<br>Connecting current classes.<br>Knowing more, linking more.<br>Influenced by present teachers. | Communication, problem solving, listening to points of view, tolerance and relating concepts. |
| P10 | Makes connections between math and physics during class.<br>Likes making those connections.<br>Realizes that mathematics can be applied. | Negative previous academic experiences with mathematics.<br>Lack of connections between math and other classes. | |
| P11 | Understands mathematics as a tool that connects with other fields. | Lacks connections and uses for career path.<br>Shaped by past experiences. | Optimism, idleness. |
| P12 | Finds it difficult to spontaneously relate mathematics. | Disconnection with everyday life.<br>Influenced by hands-on class activities. | |

## 4.5 Synergy of mathematics and physics

The entwining of mathematics with other fields of knowledge emerged as a significant way in which participants immediately recognized the interdisciplinary presence within their learning journey. While a multitude of subjects shared connections with mathematical principles, it was physics that stood out as the most prevalent and impactful domain, enriching their math class experiences. For participants, the interplay between mathematics and physics was readily observable in instances where problems explicitly showcased connections to biology, chemistry, or physics. Participant 12 eloquently captures this sentiment "In math class, I sometimes see the presence of ideas from other areas. When problems directly state the connection to biology, chemistry, or physics, I can see the presence. Different lab projects have helped me. For example, physics labs help me understand concepts more, because they are a physical representation of math and have topics applied to it."

This fusion of mathematical and physical concepts led to a profound synergy, with some participants like Participant 3 expressing, "I am in mathematics (class) and I am always thinking about physics." This dynamic perspective opened new avenues for comprehending the natural world. Participant 6 beautifully elaborates on this realization "it is much easier to understand a topic because we see mathematics'

FIGURE 4
Participants using software tools to model harmonic movement from real life videos.

nature reflected in physics. I mean, we simply understand better because we can see it in another way."

However, it is important to note that not all participants shared the same enthusiasm for the fusion of mathematics and physics. For instance, Participant 2 experienced a sense of disappointment upon recognizing that mathematics and physics operated within their own distinct frameworks. She conveyed this sentiment, stating, "when we started to see physics a lot it was like "wow, I unenrolled physics to end up studying physics in math" so I was a little bit, I do not know." Despite her initial reservations, Participant 2 managed to embrace the situation by recognizing the applicability of this interdisciplinary encounter, sharing, "well, I've been trying to catch it up and I feel that it's useful that we see real-life applications."

These nuanced perspectives highlight the diverse range of responses to the integration of mathematics and physics, reflecting the complexities and richness of interdisciplinary experiences. Just as mathematics and physics intertwine, so do the participants' perceptions, forming a tapestry of understanding that is uniquely their own.

### 4.5.1 Perspectives on textbook mathematics

The participants' perspectives on the integration of mathematics with other disciplines revealed intriguing insights into their familiarity with different pedagogical approaches and their epistemological viewpoints. Participants 1, 2, and 4 not only emphasized the importance of possessing strong foundational knowledge in mathematics and other fields to establish meaningful connections, but also highlighted their preference for alternative methods of mathematical instruction. Participant 4's viewpoint captured this sentiment succinctly "I think that it's okay that we have to understand those things (connections) however, it's something I'm not used to, I was taught like "get the book out and solve problems"." This sentiment underscores the participant's inclination toward more traditional textbook-centered methods of learning mathematics, indicating a certain level of discomfort with the interdisciplinary approach.

Furthermore, Participant 4's remark, "I feel that we take those courses separately for a reason and mathematics alone, I mean, each one (subject) should have its own space," reflects an epistemological position that advocates for the preservation of distinct disciplinary boundaries. This perspective suggests a belief in maintaining the separation of subjects, potentially rooted in the participant's perception of the unique value and integrity of each subject.

In contrast to more interdisciplinary approaches, these participants appear to be more aligned with a traditional view of mathematics education, where mathematical knowledge is compartmentalized and learned through standalone methods. Their viewpoints shed light on the diversity of pedagogical experiences and preferences among students, underlining the significance of tailoring educational methods to accommodate varying learning styles and epistemological perspectives.

## 4.6 Influence of teachers and classmates

Relevant influences for each participant's experience were attributed to previous lived experiences, prior knowledge for making new connections, class activities, and other parallel courses. Furthermore, teachers and classmates were reported to have a strong effect on the construction of reported perceptions. Regarding students' perception about teachers, they assure to "find the tutors take this seriously. Every time we see a new topic, they give us examples of other areas" (anonymous). Some students indicated teacher's function directly linked to the way in which interdisciplinary was manifested, such as Participant 5, "it depends on the role that teacher plays because they motivate you to see things from other points of view, in other ways, or they can also demotivate you."

Not only the teachers, but other educative features like teaching methods and philosophies were mentioned when thinking about positive influences for interdisciplinary experience. As it gets illustrated with the comment of Participant 9 "teachers, the kind of teaching that is used here that it is not centered, or that if it is, they give you the opportunity to think, it is not a squared system and it helps you learn." Figure 5 shows the teacher interacting with the team on the right.

Concerning classmates interacting, they marked the influence of teamwork in having the opportunity to be aware of what others think and do, one aspect that was identified as an element for interdisciplinarity too. As Participant 8 mentioned "situations where you work in teams with other people that maybe have different perspectives or ways to approach the same problem," he is aware that personal interest matters because "each person can see or focus on something and at the same time be within same topic." Students' interaction is shown in Figure 6. Also, a teacher recognized the benefits of the classmates' interactions by mentioning that "because we have students from different careers, each has a different approach to math and different ideas on the application. The learning of this ideas can broaden one's horizon on math, how and where can they be helpful."

By contrast, one particular student (Participant 1) opened up that the influence of her classmates was not the most encouraging for her progress in the class: "sometimes I say, 'oh damn, that I do not know' and then I realize that my classmates do know and I feel left behind and excluded." Fortunately, she found her way out of negative thoughts and ended up having a more complete interdisciplinary experience: "as we move along the semester, I'm finding the associations and I say 'wow, that's cool' y I feel that the exclusion, or that part in which I feel bad, well it wipes off and I remember why I like math a lot."

The influence of classmates was also evident in participants' reflections. Collaborative work and interactions with peers provided opportunities for students to engage in interdisciplinary discussions, share diverse perspectives, and learn from each other's backgrounds and

FIGURE 5
Teacher guiding and motivating students in the classroom.

FIGURE 6
Students collaboratively working and sharing their mental processes with their classmates.

knowledge. The diversity of academic backgrounds and viewpoints within the student cohort enabled a rich exchange of ideas, contributing to a more comprehensive understanding of interdisciplinary concepts. As participants engaged in team-based activities and discussions, they became aware of the several ways in which different disciplines could intersect and contribute to problem-solving. This finding resonates with the research of Jennett et al. (2017), who emphasized the importance of forming balanced interdisciplinary teams and incorporating expertise from various disciplines to foster innovative and holistic thinking.

However, it is important to note that the influence of peers was not uniformly positive for all participants. Some of the students experienced feelings of inadequacy or exclusion when comparing their knowledge to that of their classmates. This sentiment suggests the need for supportive classroom environments that foster inclusivity and provide opportunities for all students to contribute meaningfully. As demonstrated by the journey of Participant 1 from initial frustration to later appreciation, creating a space for students to explore interdisciplinary connections at their own pace and gain confidence over time can result in more positive experiences.

## 4.7 Balancing influences for optimal engagement

Overall, the findings highlight the multifaceted nature of influences that shape students' interdisciplinary experiences. The role of educators in fostering an environment conducive to interdisciplinary exploration and the contributions of classmates in enriching discussions and perspectives are critical factors. Striking a balance between these influences, while respecting diverse epistemological viewpoints, can lead to more engaging and meaningful interdisciplinary experiences. The interactions between teachers, students, and content can create a dynamic and holistic learning environment that nurtures creativity, curiosity, critical thinking, and the ability to connect knowledge across disciplinary boundaries (Madina et al., 2023). By recognizing and harnessing the power of these influences, educators can effectively guide students on a journey of interdisciplinary discovery, empowering them to explore the interconnectedness of knowledge and its real-world applications.

## 5 The essence, interdisciplinary experience

According to Moustakas "The final step in the Moustakas (1994) phenomenological method is the intuitive integration of the fundamental textural and structural descriptions into a unified statement of the essences of the experience of the phenomenon as a whole" (1994, Ch. 5). After the analysis of certain emerging topics from the textural and structural descriptions, a composite one can now be made.

- Seems that a holistic understanding of a phenomena that is itself holistic represents a complex task yet to be made. The subjective truths that constitute the interdisciplinarity lived by the twelve participants during the first-year calculus course are just brushstrokes of an emerging educational impressionist painting.
- On one thing, some tracings delineate struggle and challenge bounded in the sometimes-dazed linkages made from mathematics to other fields of knowledge and to everyday life. On the other hand, some other brushworks show that most of the participants found in interdisciplinarity useful and pleasant experiences for mathematics understanding, that I venture to claim are going to walk along with them during the rest of their university trajectories. Previous academic experiences, prior knowledge and the influence of classmates and teachers represent the canvas in which this interdisciplinary experience is created, leaving then to creativity the defiance for teachers and educational researchers to experiment with new textures, colors, and interdisciplinary painting techniques.

This study contributes to the understanding of educational interdisciplinary practices by shifting the perspective from teachers to students. Through the lens of phenomenology philosophy, it delves into both the challenges and benefits of interdisciplinarity within higher education settings, offering a comprehensive insight into the phenomenon. By offering empirical evidence of interdisciplinary engagement in a calculus course, this work further enriches the field of interdisciplinary mathematics education.

- We presume that this type of qualitative reflective methods depicts a valuable route towards the grasp of complex educational phenomena such as interdisciplinarity in higher education contexts, and so represents an opportunity for other scholars to keep on including and understanding everybody's voice.
- The development of descripted calculus class and the writing of this article was of great growth for both students and teachers involved. Their collective and individual experiences stand as evidence of growth.
- The evidence offered in this work can benefit mathematics educators and educational researchers interested in the teaching and learning of mathematics. The analysis of student experiences yields implications for integrating interdisciplinary perspectives into higher education curricula.
- The arrangement of factors and influences at play within these experiences and juxtaposing them with prior research findings, this work also contributes to comprehending the development and cultivation of complex interdisciplinary thinking.

In conclusion, this study paints a vivid picture of the interdisciplinary journey undertaken by students in a calculus class. Just as an artist navigates various shades, techniques, and inspirations to craft their masterpiece, so too do educators and researchers navigate the nuances of interdisciplinary education. The canvas of interdisciplinarity in higher education is dynamic and multifaceted, awaiting the continued exploration and innovation of those who seek to enhance the educational landscape.

### 5.1 Limitations of the study

Recognizing that phenomenological research methods is context-specific, this paper provides a glimpse into a specific time, place, participants, and researchers involved in the studied experience. The study was conducted within a specific context, namely a college calculus class in northern Mexico, which may limit the generalizability of the findings to other disciplines, levels of education, or cultural contexts. Additionally, the use of self-report measures and qualitative analysis introduces the possibility of bias and subjectivity in participants' responses and the interpretation of data.

Furthermore, the sample size of twelve participants may restrict the variability of perspectives represented in the study. The use of convenience sampling could also impact the diversity and representativeness of the participant pool. Moreover, the study's focus on the experiences of students may not capture the perspectives of educators and administrators, who play a crucial role in shaping interdisciplinary curricula and pedagogical approaches.

### 5.2 Implications and future research

Despite these limitations, the study contributes to the growing body of literature on interdisciplinary education. The findings underscore the importance of creating supportive learning environments that promote interdisciplinary thinking and provide students with opportunities to make meaningful connections between diverse disciplines. Educators can draw insights from this study to design curricula that foster cross-disciplinary understanding and collaboration.

Future research could expand the scope of investigation to include a wider range of disciplines, educational levels, and cultural contexts. Additionally, exploring the perspectives of educators and administrators could offer a more comprehensive understanding of the challenges and opportunities associated with implementing interdisciplinary approaches in higher education. Longitudinal studies tracking students' attitudes and experiences over time may provide deeper insights into the long-term impact of interdisciplinary education on students' academic and professional trajectories.

## Data availability statement

The datasets presented in this article are not readily available. Due to confidentiality, the raw data is only available to the research team. Requests to access the datasets should be directed to angeles.dominguez@tec.mx.

## Ethics statement

The study was conducted in accordance with the Declaration of Helsinki, and approved by the Ethics Committee of Tecnologico de Monterrey. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

IHA: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft. AD: Conceptualization, Methodology, Project administration, Supervision, Validation, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Engaging kindergarten pre-service teachers in the design and implementation of STEM lessons

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**Introduction:** Engaging young students in integrated STEM early on can support them to develop their competences linked to problem solving and critical thinking. Despite the importance of STEM education in younger ages, teachers still lack the skills and competences to implement STEM in their classes. The purpose of this study is to explore how pre-service kindergarten teachers (PSTs) understand STEM education, how they design lesson plans to teach STEM and how they implement STEM in their teaching.

**Methods:** Participants of the study were 21, 3rd, and 4th year students studying to become kindergarten teachers. The participants of the current study attended a Science Methods Course for Kindergarten which is a 36 h long course. Data collected included questionnaires, reflections, lesson plans, interviews, and classroom observations.

**Results:** Findings for the first research question reveal that kindergarten PSTs were not familiar with STEM education and did not have any previous experience with STEM education either as school students or during their studies at the university. Another important finding is that teachers' views on STEM education improved after the theoretical introduction to STEM, but considerable improvement and understanding of STEM education was evident after they engaged as learners in a STEM lesson specially designed for kindergarten students.

**Discussion:** Findings from the lesson plans designed by the PSTs showed that when working in groups PSTs designed lessons which offered integration between two subjects, mainly math and science. Finally, when implementing STEM lessons PSTs had similar difficulties as when designing lessons. Additionally, PSTs reported that they did not have support from their mentors, or their mentors did not act as role models during the implementation of their designs. What this study supports is the need for teacher preparation programs to prepare kindergarten teachers in understanding what STEM is, but also supporting them in the process of designing and implementing STEM lessons. Implications from this study include the design of a teacher training course to support PSTs during their studies and in their early career, but also include mentors as part of the training course to support them to act as positive role models.

KEYWORDS

**STEM education, kindergarten, pre-school, pre-service training, teacher professional development**

# 1 Introduction

STEM (Science Technology Engineering Mathematics) education has been the emphasis of many studies, with more recent studies agreeing on an integrated STEM approach which breaks the traditional boundaries between the different disciplines (Ortiz-Revilla et al., 2022). Integrated STEM is focusing on competency-based curriculum that will "prepare young people with required competences to live sustainable, fulfilled and healthy lives in the rapidly changing world of the 21st century" (Ng, 2019, p. 3). Despite the emphasis on integrated STEM, and breaking the boundaries between the disciplines, the very structured nature of curricula across countries, especially in the education of older students (i.e., secondary school) does not allow for that integration. The context of kindergarten (4–6 year old) is suitable to promote integrated STEM education, not only because of the flexibility of the curricula, but also because of the benefits that such a curricula can bring to younger students. By engaging in integrated STEM from a younger age students can develop their competences linked to problem solving, and further develop their questioning practices (Brenneman et al., 2009). Recent studies (i.e., Uğraş and Genç, 2018; Chen et al., 2021; Yıldırım, 2021) have focused on kindergarten teachers' views about STEM, and fewer studies on professional models for the development of STEM teaching competences for in-service teachers (i.e., Brenneman et al., 2019). However, there are limited studies examining how kindergarten pre-service teachers (PSTs) understand STEM, design STEM lessons, and implement them in action. According to Hapgood et al. (2020) there are still gaps in how to measure STEM learning, how to improve teachers' knowledge and how to design robust materials for kindergarten teaching and learning education. The limited understanding of the challenges that kindergarten PSTs face in understanding, designing, and implementing integrated STEM is considered as a gap, and by addressing this gap we can potentially support teacher training and teacher professional development programs.

Based on the aforementioned gap, the purpose of this study is to explore how pre-service kindergarten teachers (PSTs) understand STEM education, how they design lesson plans to teach STEM and how they implement STEM in their teaching. Specifically, the research questions guiding the study are the following:

R.Q.1. What are kindergarten PSTs views and knowledge of STEM education before and after engaging with integrated STEM?

R.Q.2. What difficulties do kindergarten PSTs have when designing a STEM lesson plan?

R.Q.3. What difficulties do kindergarten PSTs have when implementing a STEM lesson plan?

# 2 The importance of STEM education and teacher preparation

Recent initiatives in education place an emphasis on integrated STEM education (Ryu et al., 2019), which is the integration of the multiple related subjects (science, technology, engineering and mathematics). The emphasis on STEM education is linked to the need to improve students' knowledge and understanding of STEM related concepts, but also their skills and competences. It is also related to the fact that the nature of STEM blurs the lines between the disciplines (i.e., Wang et al., 2011). Changes in our society call for skills that come across the different disciplines and can potentially help the students become responsible citizens, and have the required skills to navigate the employment world when they finish school. Integrated STEM approaches which focus on skills can support students from different backgrounds and under-represented populations, including girls (Evagorou et al., 2020) even though strong evidence is still missing (Honey et al., 2014). There are different approaches in STEM education in the literature, some of which focus on a single STEM subject, and others which focus on the integration of the disciplines. One of the frameworks of quality STEM education, by Moore et al. (2014), focuses on six key elements as important: the use of authentic and motivating context; teaching which allows students to engage in engineering challenges; the space to learn from failure; include appropriate science and mathematics content; an approach that is student centered; and teaching which includes group work and communication. The Moore et al. (2014) framework is specific to integrating engineering in STEM but nevertheless is useful in identifying the pedagogical aspects that are important in integrated STEM. In the study the emphasis is on integrated STEM which is related to the integration of the different topics with an emphasis mainly on science, mathematics and technology, which requires a problem solving and inquiry-based approach (Ryu et al., 2019). In the current study engineering was not highlighted, mainly because it is not included as part of the local curricula in the kindergarten. Technology in our framework is linked with the competences highlighted in the DigComp Framework (Vuorikari et al., 2022) which include: information and data literacy, communication and collaboration, digital content creation, digital safety and problem solving. Summarizing, the STEM framework in the current study places an emphasis on a learning environment which is problem oriented, is focusing on the integrating and use of competences and knowledge from more than two disciplines (namely science, mathematics and technology) and is following the pedagogical guidelines suggested by Moore et al. (2014).

As highlighted above, the emphasis of STEM education is on developing students' competences linked with critical thinking, problem-solving, and inquiry-based learning, and supports them in understanding the connection between STEM and the real word (Labov et al., 2010; Breiner et al., 2012). Therefore, STEM education should be based on a curriculum that can "prepare young people with required competences to live sustainable, fulfilled and healthy lives in the rapidly changing world of the 21st century" (OECD, 2019, p. 3). Young kids have a natural disposition toward STEM subjects because of their natural curiosity (DeJarnette, 2018). Introducing STEM education in early years is considered important because young children ask questions and are curious to learn more about the world around them (Yıldırım, 2021). Other researchers state that important brain growth and learning takes place during early years (Catherwood, 1999) and that benefits from quality early childhood education can impact a child through their adulthood (Sylva et al., 2010) and therefore early STEM education can be critical (Campbell et al., 2018). Therefore, introducing STEM education in preschool can support students' curiosity and encourage them to learn STEM related concepts and develop skills (Yıldırım, 2018). Other researchers (Campbell et al., 2018) observed that young students' STEM experience improved their self-efficacy to learn STEM and their appreciation of STEM subjects.

STEM education should focus on developing in-service and pre-service teachers' STEM knowledge and teaching practices. Teachers should also be aware of the nature of STEM education and the complexities involved in the teaching process. One of the challenges in integrated STEM is blurring the boundaries between the different disciplines and providing a more spherical understanding of how the different fields can work together for teachers (Evagorou et al., 2020). Teacher preparation is important in order provide the necessary pedagogical guidelines to educators to enable them to understand first integrated STEM, and then to support them in their effort to design appropriate lessons and implement them in action. PSTs in secondary education are prepared on how to teach within their own field only (i.e., math, science) and are not familiar with integrated approaches (Evagorou et al., 2020). Kindergarten and primary PSTs are prepared to teach all courses of the curricula, but they are still prepared to teach the different courses separately (i.e., science, math, language). Recently, some programs have focused on preparing PSTs for integrated STEM (i.e., Ryu et al., 2019). In their study Ryu et al. (2019) designed an integrated STEM course for secondary school teachers and explored how PSTs develop integrated STEM courses and what challenges they face in developing and implementing the courses. Findings from this study support that the limited understanding by PSTs on how the subjects are linked did not allow them to integrate the subjects and they believed that if they include S, T, E, M in a way in their teaching they are doing integrated teaching. An additional finding in the same study is that PSTs lack role models and experiences of STEM activities since integrated STEM is not widely introduced in schools and therefore most of them do not have experiences either as students or as PSTs.

Other than the difficulties mentioned above, kindergarten teachers typically lack content knowledge of STEM domains and often hold negative attitudes toward STEM subjects (DeJarnette, 2018; Yıldırım, 2018). Yıldırım (2021) in their study offered an 80-h STEM training program to kindergarten teachers. The findings of this study show that kindergarten teachers understand the purpose of STEM education as supporting students to increase their creativity, problem solving, critical thinking skills and communication, and furthermore they believe that STEM can help students increase their interest in STEM. The same study by Yıldırım (2021) showed that teachers did not know how to plan a STEM lesson and had a lack of resources to support them in planning, and lack of equipment. One limitation of this study is that all views are self-reports by teachers and lesson plans were not analyzed. A similar study by DeJarnette (2018) engaged in-service teachers in professional development and explored how kindergarten teachers implement STEAM in their teaching after the professional development. The study showed that before the professional development teachers spend less time teaching the content in which they lack knowledge, but after the professional development they improved their self-efficacy but still the rate of implementation of STEAM lessons was limited. Finally, Campbell et al. (2018) explored how kindergarten educators engage preschool students in STEM. According to their findings STEM activities in preschool were presented as either mathematics or science activities and teachers' level of comfort in teaching STEM influenced how they designed the activities and some teachers mentioned that there was a "gap in their understanding about how best to integrate" (p. 23).

The findings from these studies highlight the gap in the literature when in comes to understanding PSTs difficulties in understanding and implementing STEM education with younger students, and this is what the current study aims to address.

# 3 Materials and methods

## 3.1 The context

The participants of this study were 3rd and 4th year students studying to become kindergarten teachers (specializing in 4–6-year-old students) at a private university in Cyprus. The program of study they were attending is a four-year program leading to a Bachelor in Education which covers theoretical and practical perspectives of becoming a kindergarten teacher. The program includes school practicum in kindergartens during the last 2 years of study. During the school practicum PSTs take over a classroom and are mentored by the classroom teacher and regularly observed by faculty members. The program of study does not include a STEM education course, but includes separate courses on science, math, and technology education. Engineering education is not part of the program of study as this is not included in the local kindergarten curricula. The participants of the current study attended the Science Methods Course for Kindergarten which is a 12 week-long, 3 h per week course. The course is designed to provide theoretical perspectives on teaching science to younger students, includes workshops on lesson design, and contains a practical part in which PSTs are asked to interact with younger students during a science activity in a kindergarten.

During the Fall 2021 semester in which the data for part of the study was collected, part of the course was redesigned with an emphasis on STEM education. The decision to redesign the course was based on: (a) the emphasis in research and policy to introduce STEM education in school, especially in early years (Achieve, 2013; EU STEM Coalition, 2016; European Schoolnet and Texas Instrument, 2018), and (b) the collaboration developed between the instructor of the course and two other colleagues at the Department of Education specializing on technology and math education. This collaboration led to the development of integrated STEM lesson plans that were implemented with 4–6 year old students and modified based on feedback by practicing kindergarten teachers. The integrated STEM lesson plans were used as exemplars during weeks 8–10. As part of the course, PSTs were asked to design a STEM lesson plan in groups with a duration of 4 periods of 40-min lessons, and present one of the activities in the form of microteaching to the rest of the class. The content and structure of the Science Methods Course for Kindergarten is presented in Table 1.

## 3.2 Participants

Participants for the first and second research questions were 21 PSTs in their third and fourth year of study, who attended the Science Methods Course for Kindergarten during the Fall 2021 semester. All participants were female. Students attending the BA in Kindergarten program are students who join the program with low grades from high-school, especially in the sciences (science, mathematics, technology), and negative attitudes toward the STEM disciplines. Furthermore, these students have experiences using technology for their own use (i.e., social media, to prepare an

TABLE 1 Structure and content of Science Methods Course.

| Week | Description of content |
|---|---|
| Week 1 | Introduction to science learning and the local curriculum |
| Week 2 | Introduction to students' alternative ideas, the constructivist model of learning, and socio-cultural theories of learning in science |
| Week 3 | Inquiry based learning in science |
| Week 4 | Scientific and engineering practices as presented in the Next Generation Science Standards (Achieve, 2013) and connection to STEM education |
| Week 5 | Introduction to modeling as a scientific practice (Achieve, 2013; Evagorou et al., 2020) |
| Week 6 | Designing science lesson plans for younger students based on the local curriculum with an emphasis on students' experience and questions. Providing examples of science lesson plans for 4–6 year old students |
| Week 7 | Introducing STEM and interdisciplinarity—theoretical perspectives of STEM education, benefits of STEM education and what research has to say |
| Week 8 | Engaging in an integrated STEM lesson as students and reflecting on the process |
| Week 9 | Characteristics of a STEM lesson (problem based, guided by a question, interdisciplinary, inquiry based) |
| Week 10 | Turning a science lesson into a STEM lesson (transforming science lessons from the curriculum into a STEM lesson in their groups) |
| Week 11 | Microteaching of the STEM lesson designed by the groups of students, interviews with groups and feedback on lesson by instructor |
| Week 12 | Implementing STEM activities with 4–6 year old students in a kindergarten |

TABLE 2 Profiles of case studies.

| Pseudonym of participant | Profile |
|---|---|
| Sonia (PST 2) | High achieving student, positive evaluations in 3rd year school practicum, outgoing, social, reported positive science and math experiences from school, very good technological skills, high self-reported readiness to teach science, math and use technology |
| Ariana (PST 7) | Average grades in degree, positive evaluations in 3rd year school practicum, reported positive science and math experiences from school, good technological skills, average self-reported readiness to teach science, math and use technology in the classroom |
| Lucy (PST 9) | Average grades in degree, average evaluations in 3rd year school practicum, reported positive science and math experiences from school related to outdoor activities as part of a research program, her native language is different than the language of instruction, low self-reported readiness to teach science and math, and high self-reported readiness to use technology in the classroom |

assignment) but they usually have basic technological skills. For the third research question, data were collected from three PSTs, as case studies. The decision to focus on the specific cases is based on two main criteria: (a) all three PSTs participated in the school practicum during the subsequent semester (Spring 2022) and could be observed teaching a STEM lesson in real settings, and (b) data collected during the semester indicate that all three cases had different profiles in terms of their academic performance and their understanding of STEM education. The profiles of the three participants are provided in Table 2 below.

## 3.3 Data collection

Data collection occurred during the academic year 2021–2022. During the Fall 2021 semester, the PSTs attended the Science Methods Course for Kindergarten from which the data for the first and second research question were collected. During the subsequent semester, the fourth-year PSTs, who formed the three case studies for this research, underwent their final year teaching practicum in different kindergartens. Data for the third research question were collected during the practicum.

To address the first research question, data regarding PST' perspectives on science, STEM and their readiness to teach science, mathematics and technology were collected through tests administered at the beginning, middle and end of the semester. Additionally, their understanding of STEM was assessed through written online reflections conducted at the end of week three (before they engaged with STEM activities) and at the end of week seven (after experiencing STEM activities). Regarding the second research question, lesson plans from three PSTs were collected and subjected to analysis. Furthermore, the PSTs participated in interviews focused on their lesson plans and the rationale behind their design choices. To address the final research question, the three PSTs were observed while teaching a 40-min STEM lesson during their placement. All three PSTs were interviewed to obtain their insights and reflections on the lesson after is completion. Table 3 presents an overview of the data collected for each research question.

## 3.4 Data analysis

Pre and post-test questionnaires were collected by all participants for the first research question. The first part of the questionnaire

TABLE 3 Overview of data.

| Research question | Data collected | Data collection point |
|---|---|---|
| R.Q.1. What are kindergarten PSTs views and knowledge of STEM education before and after engaging with integrated STEM? | Views and knowledge of science and STEM<br>Views about readiness to teach science, math, technology, and STEM | pre and post questionnaire (weeks 1, 7, and 12) |
| R.Q.2. What difficulties do kindergarten PSTs have when designing a STEM lesson plan? | Reflection<br>Group STEM lesson plan<br>Interview with PSTs justifying their choices for the lesson plan | Week 3 and Week 7<br>Week 11<br>Week 11 |
| R.Q.3. What difficulties do kindergarten PSTs have when implementing a STEM lesson plan? | Observation of STEM lesson taught during school practicum (for three PSTs)<br>Individual reflection interview with the three PSTs at the end of the observation | Spring semester 2022 |

TABLE 4 PSTs views on what STEM is before, during and after engaging in an integrated STEM course.

| | Week 1 $N = 21$ | Week 7 $N = 21$ | Week 12 $N = 21$ |
|---|---|---|---|
| Category 1: I do not know what STEM education is | 18 | 0 | 0 |
| Category 2: STEM is a digital platform | 1 | 0 | 0 |
| Category 3: STEM education has to do with a learning theory | 2 | 0 | 0 |
| Category 4: STEM education includes science, mathematics, technology, and engineering | 0 | 3 | 1 |
| Category 5: STEM education has to do with presenting a problem to the students and asking them to solve it using different subjects | 0 | 18 | 2 |
| Category 6: STEM education has to do with giving a problem to the students, and based on the problem organizing activities that require the skills and knowledge from different disciplines to solve | 0 | 0 | 18 |

TABLE 6 PSTs ideas about designing a STEM lesson.

| Category of response | Week 3 $N = 21$ | Week 7 $N = 21$ |
|---|---|---|
| Category 1: Do not know how to teach math, science and technology together | 5 | 0 |
| Category 2: Designed a science that will include some mathematics | 6 | 0 |
| Category 3: Designed a sink and float lesson (science) and ask the students to put the objects in categories (mathematics) | 4 | 0 |
| Category 4: Used a robot to teach to the students how to make it move and then use it as part of an assessment activity (i.e., the students give instructions to the robot to move to a place on the ground where the correct response is) | 6 | 4 |
| Category 5: Start with a problem which requires a solution | 0 | 5 |
| Category 6: Start the lesson with a problem and then organize it in a way that would require discussing math and science concepts and the use of technology | 0 | 12 |

TABLE 5 Self-reported readiness to teach science, mathematics and technology.

| Self reported readiness to... | Week 1 | | Week 12 | |
|---|---|---|---|---|
| | *M* | SD | *M* | SD |
| Teach science | 3.3 | 0.8 | 4.1 | 0.4 |
| Teach mathematics | 3.7 | 0.8 | 4.0 | 0.6 |
| Teach with the use of technology | 3.8 | 0.7 | 4.1 | 0.4 |
| Use technology themselves | 4.7 | 0.5 | 4.4 | 0.5 |

included open-ended questions. Individual responses were read looking for patterns related to views and knowledge of STEM education and responses were open coded to create the categories shown in Table 4. The questionnaire also included a part with5-point Likert scale regarding PSTs self-reported readiness. For this part the average score was calculated for all participants and results are presented in Table 5.

Regarding the second research question, the examination of PSTs difficulties when designing a lesson plan was based on: (a) the open coding of the reflective diaries, (b) open coding analysis of their lesson plans and the recordings of their interviews and presentations. The responses to the reflective diaries where read and categories were created (see first column Table 6). Lesson plans were submitted by groups of PSTs (4–5 PSTs per group) and were analyzed looking at: the problem or driving question; the objectives; the teaching approach and pedagogical strategies applied and the content and structure of the activities. During the group interviews the PSTs were asked to justify their choice of topic, the problem/question that they chose, and the teaching strategies included. They were also asked to justify why they consider their lesson to be a STEM lesson plan. Data from the interviews were transcribed and categories were constructed in several analysis cycles that required reading the transcripts several times and coding them again, comparing them with categories that were formed from the analysis of the lesson plans.

Regarding the third research question about PSTs difficulties when implementing a STEM lesson, three PSTs were chosen as case studies. The choice of the three cases was based on the following criteria: (a) the PSTs were registered in the school practicum and could teach at least one STEM lesson as part of their school practicum, and (b) they had different profiles regarding their evaluation in practicum and their views on STEM during the course (see Table 2). PST observations during their teaching were recorded on an observation sheet. The observation sheet was prepared based on the categories developed as part of the analysis of the second research question (integration of subjects, problem-based approach, application of skills by students, PSTs confidence when teaching). The purpose of the reflective interviews with the PSTs after the implementation of their lessons was to understand some of the actions taking placing during teaching. PSTs responses were transcribed and open coded.

# 4 Results

## 4.1 R.Q.1. What are kindergarten PSTs views and knowledge of STEM education before and after engaging with integrated STEM?

PSTs views and knowledge on what STEM education is was examined with the use of a questionnaire that was administered during the first week of the semester, in the middle of the semester and at the end of the semester. The results of the first part of the questionnaire, the open-ended questions are presented in Table 4. The first column in the table are the categories developed from the open-coding PSTs responses to the open-ended questions.

As shown in Table 4, the kindergarten PSTs were not familiar with STEM education and were not able to provide a description or a definition. A representative response belonging in the first category was "I have seen the term STEM before but I do not know what it means" (PST 1, Week 1).

In the middle of the semester (Week 7), after the PSTs were presented with some information about STEM education their views changed considerably. At this stage of the course the PSTs considered STEM education as an approach driven by a problem that can be solved using different subjects, but they did not refer to activities or skills and knowledge. A representative example, belonging to category 5 is the following: "Doing STEM education means presenting a problem to the classroom and engaging students with problem solving. The problem should be connected to more than science, for example also include mathematics and technology" (PST 7, Week 7).

At the end of the semester, after participating in an integrated STEM lesson as learners (week 8) and learning about the theory of STEM education, most of the PSTs (18/21) were able to define STEM education as one which involves solving a problem using skills and knowledge from different disciplines. A representative example from category 6 is the following: "When I think about STEM education I immediately think about giving a problem to my class which will act as the driving problem for my teaching. This problem will be the basis to design activities which will use skills and concepts from science, mathematics and technology" (PST 2, Week 12).

Before week 6 the PSTs were also asked to explain in an open-ended question how they could use technology with younger students in the classroom to explore their understanding of technology as a learning tool. Most of the PSTs (15/21) responded that they could use a computer and the interactive whiteboard in the classroom to show pictures or a video related to what they were teaching while fewer PSTs (6/21) talked about using a robot to teach programing skills to the students. This highlights PSTs views of technology as a tool to be used by the teacher to present content.

Table 5 presents PSTs self-reported readiness to teach science, mathematics and technology at the beginning and the end of the semester. The questions were presented in a 5-point Likert scale and PSTs were asked to explain the response in an open-ended question.

PSTs self-reported readiness to teach science, mathematics and use technology in their teaching increased after their participation in the course. However, their self-reported readiness to use technology themselves decreased after the end of the course.

## 4.2 R.Q.2. What difficulties do kindergarten PSTs have when designing a STEM lesson plan?

Before being taught about STEM education (week 1 questionnaire) PSTs were asked to consider a hypothetical scenario in which they had to teach in the same lesson concepts and skills related to math and science and include technology. They were asked to explore the local curricula for kindergarten and based on what is taught to propose a description of a lesson. The term STEM was not used in the question as PSTs initial questionnaire showed that they were not familiar with this term. PSTs responses to the reflective diary were coded using open coding and the categories developed through the process of reading all responses from the reflective diaries from weeks 3 and 7 and creating the six categories that appear on the first column on Table 6.

As shown in Table 6, PSTs do not understand the meaning of integrated STEM and cannot design an integrated STEM lesson on week 3. Five PSTs directly quote that they do not know how to design a lesson with mathematics, science, and technology, while the remaining PSTs (16/21) suggest lessons in one of the disciplines. Category 3 is specific on sink and float as all four PSTs in the specific category used the sink and float concept in their responses. This is probably linked to experiences these PSTs have from observations they have done in kindergartens earlier in their studies. A representative example from category 3 is: "I decided to teach sink and float as a STEM lesson. After asking students to experiment with different materials to see which float and which sink I will ask them to put them in two groups. I consider this last part as doing mathematics since we also do this in our maths course. So this will be my STEM lesson" (PST 5, week 3).

At the end of week 7, when the PSTs were introduced to STEM education and were presented with some examples of STEM lessons,

TABLE 7 Analysis of lesson plans developed by groups.

| | Topic and question/ problem | Objectives | Teaching approach and activities |
|---|---|---|---|
| Group 1 | Magnets: How to make a car move without pushing it? | - Asking questions about how to make the car move<br>- Explaining/ reasoning about the process of constructing a car<br>- Construct a car using knowledge from magnetism<br>- Applying measure knowledge to construct car | - Inquiry based learning<br>- Used prior knowledge from science and math<br>- Applied design based thinking for the construction of the car<br>- There is integration between the different topics and the activities are linked between them<br>- No emphasis on technology |
| Group 2 | Volcano: What are volcanoes? | - To learn about volcanoes and how they work<br>- To understand how to move a robot in the different directions<br>- To be able to sort objects based on their size | - Each activity is focusing on one of the objectives and there is no continuation or connection between them<br>- Inquiry based approach is used in each individual activity but there is no integration of the disciplines, they are taught separately |
| Group 3 | Shadows: What are shadows and how to create them? | - To learn how shadows are created<br>- To understand how to change the direction and length of a shadow<br>- To apply math knowledge to measure shadows using their own units of measurement<br>- To use a robot to sort<br>- To be able to sort objects based on their size | - There is a continuation between the activities and integration between math and science activities<br>- Inquiry based approach is used in each activity<br>- Technology is used separately in the final as a way to assess students' understanding of the topic |
| Group 4 | Light/transparency: Which objects are better to hide a present? | - To sort objects based on their transparency<br>- To predict which is the best object to use to hide a present<br>- To apply math knowledge to measure the object and create the best wrapping<br>- To use a robot to sort objects based on transparency | - There is a continuation between the activities and integration between math and science activities<br>- Inquiry based approach is used in each activity<br>- Technology is used separately in the final as a way to assess students' understanding of the topic |
| Group 5 | Bees: Why are the bees important? | - To understand the role of the bees for our environment<br>- To use a model of a bee and pollination (using Lego We Do) to explain pollination | - Inquiry based approach is used in the activities and there is a continuation between the activities<br>- Technology is used as a ready model for students to use to explore how pollination is happening in the environment<br>- There is no reference to math concepts |

they were able include in their lessons one of the main characteristics of STEM lessons, starting with a problem (5/12). More than half of the PSTs were also able to identify that the problem should be posted in a way to enable the use of math and science concepts and skills, and the use of technology. A representative example from category 6 follows: "I decided to start with a problem, a scenario. We need to create a cover for our car that is waterproof and can also fit the car. The students must experiment to understand which materials are waterproof and which not, but also need to find ways to measure the car to make a uniform that is appropriate. Therefore, I am using mathematics and science together. I will also introduce technological tools that will help them design the cover, but I need to explore this more to see how to implement it" (PST 2, week 7).

To further explore PSTs difficulties when designing STEM lesson plans, PSTs group lesson plans were analyzed. The analysis of the lesson plans is presented in Table 7.

Based on the analysis presented in Table 7, Group 1 designed a lesson which integrated science, math and engineering through the use of design thinking (students were asked to think of how to design a car, reflect on the process, evaluate their ideas and build the car with the help of the teacher). The lesson included objectives focusing on skills and STEM practices and had objectives for science, math and engineering, but technology was not used in the process. During the interview the PSTs explained that they wanted to design a lesson in which the students would work collaboratively and "engaging in the learning process in a similar way as we did when we experienced the STEM lesson as learners. We came up with this idea based on our knowledge of science but we could not think of any ways to introduce technology in a way that would make sense for the students" (Nicky, Group 1).

Group 2 designed a lesson in which activities on science and mathematics were separate and therefore there was no integration, and used technology as a tool to assess the students. When PSTs in Group 2 were asked to justify their choice of topic and question they said that "the topic of volcano is interesting for the students, this is why we chose it" and when they were asked to explain why this is a STEM lesson they responded that "this is a STEM lesson because we have objectives for science, mathematics and technology and we start with a question for the students. We could not think of other ways to use technology, maybe because we are not familiar with a many technological tools that can be used with younger students" (Ellie, Group 2).

Groups 3 and 4 lessons focused on the integration of mathematics and science only, and technology was used separately as a final activity to evaluate students with the use of a robot. During the interview PSTs from Group 3 justified their choice of topic and question saying that "this topic is part of the curriculum already so we thought that we could modify it in a way to include math and technology as well. It is a STEM lesson as we have included concepts from science, math and we are also using technology at the end as part of the final assessment activity we designed" (Maria, Group 3). Similar was the response from Group 4 members who stated that "We have asked the students to use technology at the end of the lesson as an assessment activity ad we could not find other ways to introduce it in the lesson, but we have focused on math and science knowledge and skills in our lesson using examples from the curriculum" (Silia, Group 4).

Group 5 had a different approach than the previous groups. They chose to use an already constructed robotic Lego model (Lego We Do) of the bee and pollination that was used by the students to help them understand pollination and discuss about the role of the bees in the environment. During the interview the PSTs from group 5 justified their choice to use the robotic model was since by "playing with the bee model the students can see how the bee is taking pollen from the flower and this can help them understand the process of pollination" (Mayia, Group 5). When prompted to explain why this is a STEM lesson Group 5 supported it by saying that it includes technology and science without any further explanations.

## 4.3 R.Q.3. What difficulties do kindergarten PSTs have when implementing a STEM lesson plan?

For the third research question three kindergarten PSTs were observed implementing a STEM lesson during their school practicum. All groups received feedback on the lessons they designed and could implement during school practicum if they wanted (Table 8).

All three cases taught a 40-min lesson during their placement which was observed by the instructor of the course. Sonia's lesson followed an inquiry-based approach, and the students were actively involved in the activities. After the implementation of the lesson Sonia said that "I felt confident when I was teaching the lesson because we discussed the activities with the other group members, and I was familiar with the concepts involved. We constructed the cars [combination of building blocks and magnets] ourselves in our groups when preparing the lesson, so I was familiar with the difficulties the students had in the process of constructing the cars. What I enjoyed the most was students' excitement" (Sonia). When asked why she did not use technology Sonia said "I am aware that I did not include all the subjects from STEM but I could not think of any productive ways to include technology in this lesson without losing the connection between the activities."

On the contrary, Ariana was not that confident during her teaching, and she reported that during the interview as well. She said that she was anxious that the activities would not work properly and the kids She chose to teach a different lesson than the one designed by her group because as she said, in their lesson they did not manage to integrate the different STEM subjects but they had separate activities for each one of the subjects. Despite the feedback from the instructor, Ariana reported that it was still difficult for her to think how she could change the lesson to improve it. Therefore, she chose a lesson that she had taught before (Sink/Float) and added an evaluation assignment at the end of the lesson using technology. During the interview Ariana was asked why she considers this lesson to be a STEM lesson. Ariana responded that she knows that her lesson "does not fit the STEM criteria as I am only focusing on science, but I added technology at the end to have something from the other disciplines. I did not feel comfortable trying something new with the students and as I did not try it before and did not have the support from my mentor who is not familiar with STEM." Ariana was also asked about the use of technology in her teaching (she used a robotic bee which the students directed to a correct response from those presented on the floor) and explained that she has seen her mentor use this activity in the class often and "students are excited about using the bee. So I thought that since they know how to use it already it will be easier for them and for me."

Lucy was not confident during her teaching as she reported herself during the interview: "I am not very comfortable with the language as this is not my native language and I was stressing when I was teaching." Lucy followed the lesson plan they designed as a group which integrated math and science to teach shadows. She followed an inquiry-based approach and her students were engaged in the process. The final activity, which was using a robotic bee to evaluate students' understanding (similar to what Ariana did) was not connected to the

TABLE 8 Description of cases.

| Pseudonym | Description of cases based on findings from R.Q1 and R.Q2 |
|---|---|
| Sonia (PST 2) | She was not familiar with STEM education but developed a good understanding by the end of the course, had high self-reported readiness to teach math, science and technology and high self-reported readiness to use technology herself. Sonia was part of Group 1 in lesson design. When observed during the practicum she implemented the lesson as designed by her group |
| Ariana (PST 7) | She was not familiar with STEM education but developed a good understanding by the end of the course, had average self-reported readiness to teach math, science and technology and low self-reported readiness to use technology herself, none of which improved. Sonia was part of Group 2 in lesson design. When observed during the practicum she implemented a lesson from the curriculum which she thought was STEM |
| Lucy (PST 9) | She was not familiar with STEM education but developed an average by the end of the course (start with a problem), had average self-reported readiness to teach math, science and technology and average self-reported readiness to use technology herself, none of which improved. Lucy was part of Group 3 in lesson design. When observed during the practicum she implemented the lesson as designed and presented by her group |

activities she did before. When asked about her lesson during the interview she said that it was STEM because of math, science and technology and she considered that all three subjects were integrated. Lucy said "I taught the lesson in the way we designed. When I saw my mentor use the robot bee I was convinced that this was a good use of technology." When she was asked about the objective supporting the use of the robot bee, she connected this to the evaluation of the lesson and not to learning digital skills.

# 5 Discussion

## 5.1 R.Q.1. What are kindergarten PSTs views and knowledge of STEM education before and after engaging with integrated STEM?

Findings for the first research question reveal that kindergarten PSTs were not familiar with STEM education and did not have any previous experience with STEM education either as school students or during their studies at the university. The PSTs were familiar with the different subjects of STEM, and were taught these subjects as part of their school curricula, but the term STEM was not familiar to them. This can be expected since in their educational system STEM education (emphasis on integrated STEM) was just recently introduced for students in primary and early secondary schools. Furthermore, the program of study at the university does not have a dedicated course on STEM Education. This finding is similar to previous studies which highlight PSTs and teachers' lack of knowledge and understanding of STEM education (DeJarnette, 2018) and highlight the need for teacher preparation programs to focus on the preparation of PSTs to familiarize them with STEM education and the different educational principles (Yıldırım, 2021). This need has been highlighted in various policy reports, with a special emphasis on preparing pre-and in-service teachers to support students across all educational levels (National Academy of Engineering and National Research Council [NAE/NRC], 2014).

Another important finding is that teachers views on STEM education progressed after the theoretical introduction to STEM, but considerable improvement and understanding of STEM education was evident after they engaged as learners in a STEM lesson specially designed for kindergarten students (week 8). At the end of the course the PSTs were able to explain what a STEM approach is and provide multiple examples on how to apply it to their lessons. This finding is similar to findings from previous studies (i.e., Chen et al., 2021; Yıldırım, 2021) which highlight the need for PSTs to engage as learners to be able to reflect on the structure of a lesson and the difficulties that their students might have. Previous studies (i.e., Yıldırım, 2021) have also highlighted the need for professional development on STEM education for kindergarten PSTs, but also the need to support them during the design stage of developing their lessons.

A third finding is related to PSTs' self-reported readiness to teach the different subjects separately (science, math and incorporate technology) that was improved at the end of course. Their self-reported readiness to use technology themselves declined. One hypothesis is that PSTs were not familiar with many types of technologies that can be used in the classroom as tools to support in the learning process (i.e., augmented reality tools, VR tools, programming robots, programming apps) and could not understand the complexities of using these technologies before the course. Through the activities of the course which involved among other using different types of technologies as part of the lesson they could realize the levels of complexity. This finding highlights the need to acquainting PSTs with different technological tools and support them to use them themselves as learners first, and then develop the competence to use them as part of the teaching process.

## 5.2 R.Q.2. What difficulties do kindergarten PSTs have when designing a STEM lesson plan?

Findings for the second research question show that PSTs were not familiar with designing integrated STEM education lesson plans, and this can be expected given that they were not familiar with STEM education at the begging of the semester. This finding has been recorded in previous studies which explored kindergarten PSTs ability to design lesson plans (i.e., Yıldırım, 2018). PSTs showed an improved ability to design lessons after engaging with main concepts and pedagogical strategies linked with STEM during week 7, but still their understanding of a STEM lesson is mainly linked to the fact that this should be starting with a problem, and some understand the need to link this problem to knowledge and skills from math, science and technology. Findings from the group lesson plans that were designed and presented during week 11 show that when working in groups PSTs designed lessons which offered integration between two subjects, mainly math and science. One hypothesis is that PSTs are more familiar with these two subjects and therefore can more easily find connections between the two. Another hypothesis is that for both subjects they had access to the local curricula which offers examples of lesson plans, and by using these examples they could more easily adapt them to consider integration. This finding, of STEM lessons focusing mostly on the subjects on math and science only is reported elsewhere in the literature as well (Ryu et al., 2019). An additional finding from the lesson plans is that technology is used in the lessons as a presentation tool, and not as an actual tool that can be used for the students to help them improve their digital competences. One hypothesis for this finding, which is supported by the findings from the first research question, is that PSTs do not have knowledge of technological tools and how they can used in the teaching.

## 5.3 R.Q.3. What difficulties do kindergarten PSTs have when implementing a STEM lesson plan?

The case studies show that two of the PSTs designed integrated STEM lessons, with one of them focusing on the integration of two topics, science, and math, and the other focusing on the inclusion of engineering as well through, and one of them was not able to integrate any of the subjects. Findings for the third research questions show that only one of the PSTs was able to implement the lesson as designed, placing an emphasis on problem-based learning and inquiry approach integrating three of the disciplines. One of the PSTs chose to teach a science only lesson that was different from the one they designed in their group. She made this decision because she did not feel confident and did not have support from her mentor, who was not familiar with STEM. The third PST taught a science and math lesson which used technology as a presentation or assessment tool. The findings from the third research question show that PSTs have difficulties in implementing a STEM lesson in their class. Their self-reported readiness to teach the subjects separately might be a predictor on their uptake of the lessons and how they implement them. This can be supported by the finding that considering that Sonia (case study 1) who had higher self-reported readiness was better in designing and implementing the lesson. This has been highlighted in the literature before and is connected with PSTs' self-efficacy (Campbell et al., 2018) which seems to predict their ability to teach. Another important finding from the third research question is PSTs lack of understanding on how to use technology with their students in the class. None of the PSTs has used technology in a way that promotes students' digital skills and as already mentioned in the findings for the first research question this might be related to their lack of knowledge of technological tools.

## 6 Conclusion

STEM education is becoming more popular, as the integrated STEM approach can help students acquire 21st century skills and competences. The need to start introducing integrated STEM approaches from an early age is linked to the need to provide skills and dispositions from an early age (OECD, 2019). The findings of the current study shed light on early years education, and on the fact that kindergarten PSTs lack the skills, knowledge and self-efficacy that can support them in developing and teaching STEM lessons. This finding is not irrelevant from teacher educators' lack of cohesive understanding of STEM education (Kelley and Knowles, 2016), or the fact that a coherent STEM education framework is not agreed upon between researchers, educators and policy makers (Evagorou et al., 2020). What this study supports is the need for a coherent STEM education framework, and preparation of STEM educators to introduce STEM. Furthermore, what is highlighted is the need for teacher preparation programs in line with new views in training (Putnam and Borko, 2000). These programs should focus on preparing kindergarten teachers to understand what STEM is, but also support them in the process of designing and implementing STEM lessons. Furthermore, in order for the PSTs to be able to design STEM lessons, knowledge of the different disciplines involved in STEM should be acquired, both from the perspective of a learner (Campbell et al., 2018), and the perspective of an educator (Evagorou et al., 2020). The modified model of development proposed as a reflection from the findings of the study is for PSTs to be engaged in STEM as learners first, with an emphasis on all different STEM subjects, and then reflect of the process and the pedagogical practices that were used in the process. In this way PSTs will acquire the knowledge and pedagogical practices that will help them improve their readiness and self-efficacy to teach STEM. Furthermore, during their development PSTs need to engage in examples of STEM teaching in schools, something that is lacking based of the findings of this study. Therefore, mentors should also participate in professional development using a similar structure a PSTs, and supported in implementing STEM activities in their classes as role models of kindergarten PSTs. Implications from this study include the design of a teacher training courses to support PSTs during their studies and also in their early career, but also include mentors as part of the training course to support them acting as positive role models.

Limitations of the study include the emphasis on the science, mathematics and technology practices only, excluding engineering practices. This is mainly due to the structure of the local curricula which does not include engineering practices, on the emphasis of the course on science methods and the expertise of the departmental team which does not include an engineering expert.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical approval was not required for the studies involving humans because there was no ethical approval requirement at the institution for participants over 18. Only informed consent by the participants was required. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

## Author contributions

ME: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Investigation, Methodology.

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The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Game-Based Learning experiences in primary mathematics education

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Using game-based learning (GBL), especially digital game-based learning (DGBL), as a teaching and learning environment can be a pedagogical resource and a good strategy in the classroom to support mathematical learning. Effective manipulatives and games play a crucial role in promoting mathematical understanding. They support students in building, reinforcing and connecting varied representations of mathematical concepts. High-quality games are particularly valuable for learners as they provide them with control and adaptability. These games have properties that are adapted to cognitive and mathematical structures, facilitating the development of connections between different pieces and forms of knowledge. Digital games can help to achieve the same effects. In this paper, we conduct a quasi-experiment using games developed for this purpose. Our aim is to investigate whether non-digital games vs. digital games yield different results. Our results indicate that while students enjoyed themselves and found the task-solving enjoyable during both types of game-based learning, the use of non-digital games vs. digital games can sometimes lead to different outcomes.

KEYWORDS

**game-based learning, digital game-based learning, digital games, non-digital games, STEM, manipulatives, concrete, virtual**

## 1 Introduction

According to Rosli et al. (2015) prekindergarten, kindergarten, and elementary school teachers use both tangible and virtual manipulatives as instructional aides to facilitate student understanding of concepts in numbers, operations, geometry, algebra, measurements, data analysis, and probability. Tangible manipulatives assist students in constructing, reinforcing, and linking diverse mathematical concepts. From literature, engaging in concrete activities serves as a beneficial mental exercise (Clements, 1989; Kamii, 1989). Clements (1999) found that for teachers to actively engage children's thinking, manipulatives must be integrated into educational tasks to provide meaningful context and support, alone they are not enough. "Games are effective not because of what they are, but because of what they embody and what learners are doing as they play a game" (Van Eck, 2006, p. 18). According to Russo and Russo (2018) and Russo et al. (2023), the six principles of educationally rich mathematical games in the literature are: 1. Students are engaged; 2. There is a balance of skill and luck. 3. Mathematics is central. 4. Flexibility in learning and teaching. 5. Promotes home-school connections. 6. Games into studies. The educational value of a game depends on the extent to which teachers perceive that a game is appropriately challenging, engaging, enjoyable, adaptable to support different learners, and adaptable to inquiry or broader mathematical investigations. Likewise, perceived levels of student enjoyment and engagement, as well as the potential of a game leads to rich mathematical inquiry, were important features in assessing how likely a teacher would be using a particular game with students in the future if given the opportunity, as was the game's ability to support mathematical discussion. Research by Bordás (2016) shows that in order to motivate students and adapt to their individual needs, teachers at both lower and upper secondary level consider it important to use interactive methods, game-based teaching and the use of the internet and digital tools.

In practice, primary school teachers tend to use non-digital mathematical games to support maths learning (board, dice, and card games). According to Russo and Russo (2020) and Russo et al. (2021) almost all the primary teachers admitted playing mathematical games in their classrooms a minimum of once a week, they view games as highly effective for developing all four proficiencies highlighted in the Mathematics Curriculum: fluency, understanding, problem-solving, and reasoning. According to Dienes (2015), activities, games and concrete experiences should be the base of learning mathematics, that could be a joyful experience with the use of tools that enhance efficiency. In primary school, children establish connections between abstract concepts and practical experiences in a more tangible manner, experiencing them through games. Manipulatives are "objects designed to represent explicitly and concretely mathematical ideas that are abstract" (Moyer, 2001, p. 176). Rosli et al. (2015) said that manipulatives help students to see the connections between concepts and improve their knowledge in problem solving and problem posing, even in the case of real-life problems. The incorporation of games serves as a compelling tool in the process of learning mathematics. Di Sia (2017) found that the association with games stimulates children's imagination, providing an enjoyable approach to mathematics, that is perceived as a helpful and enjoyable discipline. Students enjoy the tasks, where they have to invest mental effort in the use of games, didactic materials (Yung and Paas, 2015).

The virtual tool does not seem suitable for this. Öztop (2022) examining the impact of using games in primary school mathematics education on learning outcomes and comparing effect sizes by game type finds that the effect of digital games is small (0.436) and that of non-digital games is large (1.032). The results show that non-digital games are much more effective on learning outcomes than digital games in primary school mathematics education.

According to the literature, there is a contrast between the frequency that teachers prefer to use non-digital games with students vis-a-vis the tendency in the literature to focus on digital games, where the majority of research focused on game-based learning in mathematics, specifically tend to explicitly focus on digital games, rather than non-digital games (Hainey et al., 2016; Hussein et al., 2022). The large scale of quantitative studies involving non-digital games are comparatively rare, with most studies into games occurring within a single school context, generally involving students from a limited range of specific grade levels.

Guiding the pedagogical practice of teacher trainees as their supervisor, we created our own development games and we implemented together with the students in classrooms where they teach, and then we examined the experiences and results together. Our question is: whether non-digital games vs. digital games are different?

## 2 Digital games, digital game-based learning and achievements in learning of mathematics

According to the literature, numerous studies have identified positive impacts associated with the use of games in learning mathematics (Suh et al., 2005; Steen et al., 2006; Moyer-Packenham et al., 2008). Such activities are typically interactive, motivating, and practical, contributing to maintaining students' interest and enhancing their understanding of mathematical concepts. The aim is to integrate games into the educational environment to enhance students' mathematical learning, expanding the use of games based on higher-order thinking can diversify the educational benefits of games and serve a wider range of learning objectives. Kailani et al. (2019) found that the games, by themselves, do not automatically imply positive impact. One must consider the diverse factors that work in tandem with game-based learning. Such factors include the technical aptitude and attitudes of the people—classroom teachers, faculty members, parents, and researchers—implementing the technology. Not only should there be an effective implementation plan that is well-executed, but the content of that execution needs to be well-designed with thorough curricula relevance.

Game-based learning means the use of games for educative purposes and aimed to improve the user knowledge and experience. The main benefit of these educational games is they focus on improving children's life-essential abilities such as problem solving and critical thinking. GBL aimed to improve the user's knowledge and experience.

*Digital game-based learning (DGBL)* is learning by using certain computer games for educational purposes. It is a type of game-based learning (GBL; Prensky, 2001). Computer games can be used as a "learning tool" (Ke, 2008, p. 1609) that "simulate real-life social networks" (Neville et al., 2009, p. 410; Ferguson, 2014) and motivational situations such as the use of real-world and computer-generated data to perform math operations.

The contemporary epistemological and pedagogical viewpoints in mathematical education highlight the importance of incorporating realistic mathematical practices and sense-making experiences. Problem solving is a major component of "thinking mathematically" (Schoenfeld, 2020). A DGBL activity engages students in the process of problem solving or knowledge acquisition when facing the challenges presented by the game (Huang et al., 2010). Literature suggests that DGBL stands out as a promising approach for enhancing students' learning motivation and achievement in mathematics. The computer games in terms of being interactive, based on a set of agreed rules and constraints, and directed toward a clear goal and constantly provide feedback, either as a score, toenable players to monitor their progress toward the goal (Clark et al., 2016) DGBL demonstrates positive impacts on learning across diverse subjects and for various types of learners. Its motivational aspect significantly engages and captivates learners. Additionally, DGBL actively supports, reinforces, and expedites the learning process, contributing to the development of higher-order cognitive skills (Hong et al., 2009). "The game playing process therefore supports the learning process by allowing players to acquire learning experiences in games, encouraging interactions between learners and the game system, and situating learners in complex learning environments" (Huang, 2011, p. 694). Twigg (2011) emphasized the essential integration of technology into mathematics curriculum, asserting its necessity for student learning in contemporary society. Accordingly, the utilization of interactive software and computers emerges as crucial tools in facilitating math learning through practical engagement. Ferguson (2014) found that DGBL can offer students the opportunity to enhance their current knowledge when teachers provide the right DGBL environment relevant to the curriculum being learned. Hung et al. (2014) stated that supplying practice opportunities along with immediate feedback through the use of computer and information technologies proves to be effective in encouraging students to enhance their understanding of mathematics.

Teed (2012) asserts that DGBL or GBL unfolds within a virtual environment enriched with fantasy elements, involving participants in educational activities through the utilization of technological tools like computers. DGBL specifically employs digital games to instigate competition, captivate learners, and provide challenges, ultimately serving as a motivational and engaging medium for learning.

Trybus (2015) claims that GBL has many advantages. It offers cost-effectiveness, minimal physical risk or liability to learners, standardized assessments for facilitating student-to-student comparisons, high levels of engagement, a learning pace customized to individual student needs, immediate feedback responses to errors, seamless transfer of learning to real-world scenarios, and an overall engaging experience for the learner.

Gillispie et al. (2010) observed that students exhibited an average increase of 17% in math achievement when 500 middle school students were examined regarding their achievement and attitudes while using problem-based digital games that incorporated concepts in prealgebra and algebra. The study found that students were not only receptive to repeating GBL missions but were also willing to engage in them to enhance their scores on the computer.

In a quantitative study (Roschelle et al., 2010) the aim was to assess whether the utilization of computer software led to increased student engagement in mathematics class and enhanced learning for fourth-grade students. The results indicated that students in the experimental group, those exposed to the computer software, achieved higher scores on the post-test compared to students in the control group. In a mixed-methods study, Sardone and Devlin-Scherer (2010) involving 25 undergraduate students in teacher education to identify twenty-first-century skills utilized in educational games. The participants evaluated 50 games based on specific criteria such as motivation, critical thinking, problem-solving, collaboration, and communication. The findings revealed that digital games inherently incorporate many of these twenty-first-century skills. Ke (2008) identified that game design plays a crucial role in shaping students' interaction with the game.

In their meta-analysis, Li and Ma (2010) explored the impact of computer technology on the learning of mathematics in kindergarten through 12th grade students. Their findings revealed a generally positive correlation between students' academic achievement and the utilization of GBL, particularly among special needs students, elementary students, and those in a constructivism classroom setting.

Several studies have examined the effects of GBL teaching method on students' achievements, emphasizing the significance of its effects on the development of students' affective domain, which is closely linked to the subject and its instruction. A systematic review by Divjak and Tomic (2011) of 27 studies identified from the years 1995 to 2010, focusing on game-based learning (GBL) in mathematics education. Their findings indicated that math learning games not only facilitated the achievement of specific learning objectives but also enhanced students' motivation and fostered positive attitudes toward learning mathematics.

In a one-shot case study (Khan and Chishti, 2011) the objective was to examine the impact of students' active participation on math achievement. Employing a posttest-only design, the study revealed a significant correlation, indicating that students' active engagement in math class had a considerable influence on their math achievement. In his study Ferguson (2014) presented statistical significance for the use of traditional mathematics teaching methods over the use of DGBL in combination with traditional mathematics teaching methods.

Wouters et al. (2013) found that serious games were more effective than conventional instruction in terms of learning and retention, but found no evidence that they were more motivating.

Clark et al. (2016) suggests that game environments support overall improvements in intrapersonal learning outcomes compared to non-game educational environments, and that game designers and educational researchers should collaborate on designs to keep game graphics, environments, and narratives optimally aligned with assessed learning objectives. In an action research study (White and McCoy, 2019) which explored game-based learning as fifth grade mathematics students utilizing game-based lessons, results revealed that student attitudes improved both toward the lessons and toward math in general. Indriani et al. (2019) aimed to describe the quality of problem based learning assisted by Monopoly games on students critical thinking skill for seventh grade students shows that implementation PBL assisted by *Monopoly game* improve the students' mathematical critical thinking skills.

The results of a systematic review (Vankúš, 2021) with the use of 57 journals, indicate that 54% of the articles consider the affective domain in the measurement of the effects of game-based learning in mathematics education. These articles report mostly (84%) the positive influences of game-based learning on students' motivation, engagement, attitudes, enjoyment, and state of flow.

Manzano-León et al. (2021) in their systematic review in three multidisciplinary databases, on quantitative experimental studies that explore the impact of educational gamification on student motivation and academic performance in the last 5 years (40 studies), most of them report gamification as a valid learning strategy and the results support the conclusion that educational games have a potential impact on the academic performance, commitment, and motivation of students.

Erşen and Ergül (2022) analyzed 80 research studies conducted between 2017 and 2021 on games and mathematical teaching using qualitative methods. As a result, studies aimed at determining effect gained importance, and in the methodological context, quantitative studies were frequently preferred and experimental designs were used accordingly. It was also found that secondary school students were preferred as participants, that the most common type of game used was digital computer games, that the games were mostly associated with the learning area of "numbers and operations," and that the research studies had mostly positive results for the use of games in mathematics education.

According to Pan et al. (2022), in the recent decade, over 20 major literature reviews have explored the effects of learning games on students' performances, only six of these reviews focused on mathematical education. Mathematics educators generally agree that teaching and learning mathematics requires different skills compared to other subject matters. As such, games designed and employed for mathematics education can differ from those for other subject matters.

In a quantitative meta-analysis review of 24 studies, Tokac et al. (2019) investigated the effects of learning video games on mathematics achievement of PreK-12th grade students compared to traditional classroom methods. Results showed heterogeneity among effect sizes, both in magnitude and direction and suggested that mathematics video games contributed to higher learning gains as compared to traditional instructional methods.

Kailani et al. (2019) in a sistematic review of the literature found that in 12 out of the 14 studies had participants from the age group of 6–14, while two studies had a sample population of undergraduate students between the ages of 17–20. The focus of research on games is mainly in the early years of primary school, as games are rarely used in secondary school mathematics and with university students.

# 3 Research methodology

Our aim is to investigate whether non-digital games vs. digital games yield different results. Our research was based on three mathematical games. Random sampling was used: a group of students used non-digital (card-based) games, the other group used a DGBL test on computers in the informatics lab. All participants worked an hour and were supervised during the test by us. Participation in the experiment was voluntary. For the elementary school students, the teacher requested parental consent, and all of them agreed.

## 3.1 Participants

The data was collected in 2022 and 103 individuals, 9–11-year-old elementary school students participated from three schools in Western Region of Romania. Distribution of elementary students according to methods: 49 students (47.57%) used DGBL and 54 (52.42%) used non-digital games.

## 3.2 Instrument

In the literature we found that majority of teachers prefer arithmetic operations with numbers focused games in their classes. Therefore, we wanted to choose a less used area (e.g., measurement and logic).

The games designed by us could be classified to different mathematical content areas: 1st problem: focuses on numbers, logic, strategy; 2nd problem: geometry, strategy, and measurement, 3rd problem: propositional logic and reasoning.

The universal online platform that was used for the DGBL test was created within JavaScript, PHP, HTML, and CSS, which made screenshots of the final solutions. As non-digital games we used different paper cards. For assessment we analyzed the screenshots. The maximum points the participants could reach was 100 for each problem. Once students clicked the "Completed" button, the solution was saved in the database as screenshots. Participants also had the option to use the "Start "gain" button.

Our research tool included the following tasks:

1. The hexagon problem (Figure 1). *Place the small hexagons into the large shape so that adjacent triangles contain the same number (triangles are considered adjacent if they share a side). The hexagons cannot be rotated* (Marchis, 2013, p. 64).
2. The cake problem (Figure 2). *The figure represents a lattice cake consisting of 20 equal- size squares. Five friends wish to share the cake in such manner that each of them gets a*

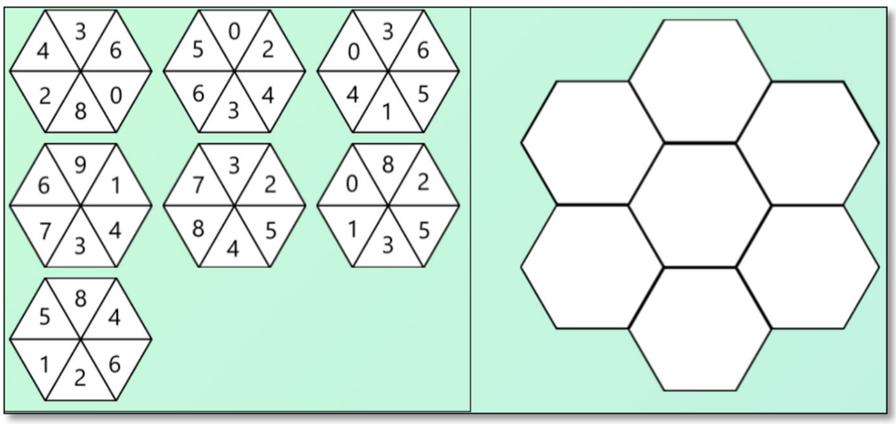

FIGURE 1
The hexagon problem.

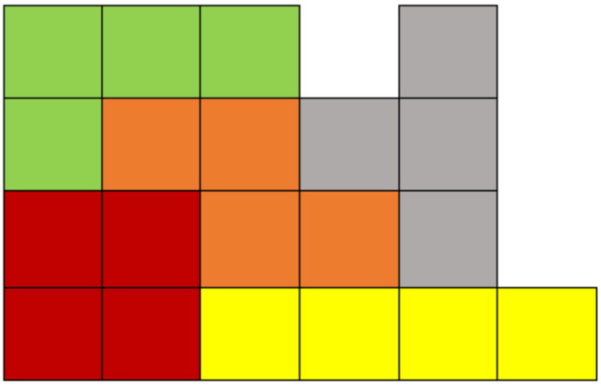

FIGURE 2
The correct solution of the cake problem (Matlap, 2018b, p. 384).

*differently shaped four-square piece. Could you help them out?* (Matlap, 2018a, p. 308).

3. The house problem (Figure 3). *There are five houses in five different colors. Each house is inhabited by a person of a different nationality. Each owner prefers a certain beverage, has a different hobby and keeps a certain pet. No owner drinks the same beverage, has the same pet, or has the same hobby as their neighbor. What we know is:*

    1. The British lives in a red house.
    2. The Swedish has a dog.
    3. The Danish drinks tea.
    4. The German plays the piano.
    5. The Norwegian lives in the first house.
    6. The green house's owner drinks coffee.
    7. The owner who plays golf likes juice.
    8. The owner of the yellow house plays football in his free time.
    9. The owner who dances has a parrot.
    10. The man who lives in the middle house drinks tea.
    11. The owner who plays board games lives next to the one that has a cat.
    12. The man who has a horse, lives next to the one who plays football.
    13. The Norwegian lives next to the blue house.
    14. The owner who plays board games is the neighbor of the one who drinks water.
    15. The green house is next to the white house, on the left.

*Who owns the fish?* (Székely, 2012, p. 53). The problems and their solutions can be found in the Supplementary file.

## 3.3 Hypotheses

The research questions of the study is: whether non-digital games vs. digital games are different? The assigned null hypothesis was as follows: H0: There will be no statistically significant difference in student achievement between students assessed with non-digital games and students assessed with digital games.

# 4 Results

## 4.1 Results of the first problem

The first task was to arrange seven hexagon-shaped pieces in accordance with specific rules. Various strategies can be employed to solve this problem; participants may attempt to locate the middle piece, initiate the arrangement from the sides, or employ trial-and-error methods. Despite placing significant emphasis on carefully reading and following the rules, many students, including undergraduates, failed to adhere to the instructions (e.g., they want to rotate pieces).

Majority of participants, 61 individuals (59.22%), successfully solved the problem, while 42 participants (40.77%) did not.

Among the elementary school students who worked with cards (54 students), 18 students (33.33%) successfully solved the problem, while two-thirds (36 students, 66.66%), were unsuccessful. On the other hand, of the elementary school students engaged in DGBL, a substantial majority (43 students, 87.76%), solved the problem, only six students (12.24%) failed. There was a significant difference in achievement between digital games and cards for elementary school students, as indicated by the statistical analysis [$t_{(103)} = 6.67$, $p < 0.05$].

The Table 1 shows the results.

## 4.2 Results of the second problem

The second problem serves as a prime example of manipulating plane shapes, with only one correct solution. Nearly all participants correctly interpreted the problem, but the challenge lay in finding the perfect solution. The task required participants to put five different shapes into the grid, essentially cutting the "cake" into five pieces. Consequently, the maximum score was 5, which was transformed into a percentage. For instance, achieving 5/5 corresponded to 100%, 4/5 to 80%, and so forth. The detailed results are presented in Table 2, revealing that the majority (76 students, 73.78%) achieved scores between 60 and 80%.

Table 2 also indicates that perfect results were attained by six elementary students: five working with non- digital games (9.25%) and one student with DGBL (2.04%). In comparison of the averages presented in Table 2, with $F$-tests and $t$-tests applied, the results achieved by the two groups of elementary school students are significantly different: DGBL solvers outperformed non-digital solvers, as indicated by $t_{(103)} = 2.08$, $p < 0.05$.

## 4.3 Results of the third problem

The final task involved a logic puzzle that measured propositional logic thinking. There are five houses of different colors next to each other and houses have to arranged in a particular order. Only two participants (1.94%) successfully solved the problem, while 6 (5.82%) either failed or gave up. The remaining students demonstrated varying degrees of success in solving the problem. Some students who use non-digital game, employed interesting problem-solving methods, such as placing


FIGURE 3
The solution for the house problem.

TABLE 1 Results of the first problem.

| Solutions | Elementary students, non-digital games | Elementary students, digital games | Total |
|---|---|---|---|
| Correct solutions | 18 (33.33%) | 43 (87.76%) | 61 (59.22%) |
| Wrong solutions | 36 (66.66%) | 6 (12.24%) | 42 (40.77%) |
| Total | 54 | 49 | 103 (100%) |

TABLE 2 Results of the second problem.

| Proportion of the correct solution | Elementary students, non-digital games | Elementary students, digital games | Total |
|---|---|---|---|
| 100% | 5 | 1 | 6 |
| 80% | 18 | 22 | 40 |
| 60% | 12 | 24 | 36 |
| 40% | 15 | 2 | 17 |
| 20% | 1 | 0 | 1 |
| 0% | 3 | 0 | 3 |
| Total | 54 | 49 | 103 (100%) |
| Average | 60.74 | 68.98 | 74.75 |

cards in a chart, while others used the floor space, stating the need for more room to process the task.

Table 3 provides detailed data on the results obtained by the groups of participants, revealing that 89.32% of them (92 students) achieved <50%.

## 5 Discussion

In our experiment two different groups was tested: a group of students used non-digital (card-based) games, the other group used a DGBL test. The large scale quantitative studies involving non-digital games are comparatively rare, in our case majority, 54 participants use non-digital games (52.42% of students involved).

TABLE 3 Results of the third problem.

| Proportion of the correct solution | Elementary students, non-digital games | Elementary students, digital games | Total |
|---|---|---|---|
| 100% | 1 | 1 | 2 |
| 75–99% | 1 | 1 | 2 |
| 50–74% | 5 | 2 | 7 |
| 25–49% | 27 | 16 | 43 |
| 0–24% | 19 | 24 | 43 |
| 0% | 1 | 5 | 6 |
| Total | 54 | 49 | 103 (100%) |
| Average | 32.15 | 25.96 | 28.30 |

The games designed by us could be classified to different content areas: numbers, geometry, strategy and measurement, propositional logic, and reasoning. These tasks are problem-type, hence more challenging, from a topic that is encountered less frequently and can be solved by elementary school students. However, when designing the games, it was possible to represent them in a plane, which is why we chose these.

The hypothesis: there will be no statistically significant difference in student achievement between students assessed with non-digital games and students assessed with digital games.

In case of the first problem: elementary school students demonstrated better results with DGBL, 43 students (87.76%) solved the problem. With non-digital games 18 elementary students (33.33%) solved the problem. There is a significant difference in achievement between digital and non-digital games for elementary school students, as indicated by the statistical analysis [$t_{(103)} = 6.67$, $p < 0.05$]. In their case, for this problem the digital game resulted in better solutions.

In case of the second problem, perfect results were attained by six elementary students: five working with non- digital games (9.25%) and one student with DGBL (2.04%). The average of elementary students who worked with non-digital games was 60.74, while for those who used digital games, the average was 68.98. There is a significant difference in the averages of the two groups of elementary school students: DGBL solvers outperformed non-digital solvers. In their case, the DGBL was the best game to resolve the problem.

In case of the third problem: two participants (1.94%) solved the problem, 89.32% (92 students) achieved <50%, while 6 (5.82%) either failed or gave up. The average of elementary students who worked with non-digital games was 32.15, while for those who used digital games, the average was 25.96. $F$-tests and $t$-tests were conducted on the achievements of the two groups of elementary students, revealing no significant difference: $t_{(103)} = 1.62, p < 0.05$ between their achievements.

When solving the third problem, we observed the following about the way of thinking: young schoolchildren treated logical statements more rigidly (they considered them in sequence, one after the other, if they encountered an obstacle, they did not overturn their previous assumptions). We observed that young schoolchildren were not flexible; they thought strictly in sequence, not preferring any particular statements, and did not pair statements. Some students who use non-digital game, employed interesting problem-solving methods.

Consequently, it can be concluded that the hypothesis is not confirmed for the 1st and 2nd problem, in case of elementary students for these problems the digital games were more effective. In case of the 3rd problem the null hypothesis was confirmed, is no statistically significant difference in student achievement between students assessed with non-digital games and students assessed with digital games.

During the experiment, we noticed that most of the participants enjoyed working both with the cards and with the digital games. The games were useful in engaging students in solving tasks. We conclude that can be a difference between the performance of students using non-digital games vs. students assessed digital games, there are tasks for which digital games help the learner, enabling them to solve them more successfully. Our results indicate that while students enjoyed themselves and found the task-solving enjoyable during both types of game-based learning, the use of non-digital games vs. digital games can sometimes lead to different outcomes.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical approval was not required for the study involving humans in accordance with the local legislation and institutional requirements. Written informed consent for participation in the study was not required from the participants and/or their legal guardians/next of kin in accordance with the national legislation and the institutional requirements.

## Author contributions

ED: Conceptualization, Data curation, Investigation, Methodology, Supervision, Visualization, Writing – original draft.

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## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/feduc.2024.1331312/full#supplementary-material

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# Virtual reality in the classroom: a difficult but exciting adventure for teachers and students

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Virtual reality (VR) enables the creation of immersive and interactive learning environments for students and teachers. This article reports on an exploratory teaching practice conducted with pre-service secondary school teachers using Neotrie, a dynamic geometry software in virtual reality. In small groups, future teachers must learn how to use the software and design a didactic sequence to bring to the classroom. Following a research-action methodology, through this experience it is reported both the advantages and difficulties encountered when starting to use VR to design didactic sequences, as well as when learning a VR sandbox software with interactive tools, like Neotrie. A proposal for assessing the sequences under the premises of the TPaCK model is also included.

KEYWORDS

**instruction, education, virtual reality, immersive learning, geometry, TPaCK, action research**

## 1 Introduction

There are currently new technologies that allow us to solve some of society's challenges and entertainment in a completely new way.[1] Martín-Gutiérrez et al. (2017) state that "the huge possibilities of accessible virtual technologies will make it possible to break the boundaries of formal education". In particular, the immersive experience offered by virtual reality in the classroom is highly engaging and motivating for students, with proven advantages in numerous previous experiences and research (Perri et al., 2021; Yünkül, 2022). This is, ultimately, the most important thing and what encourages teachers to dare to implement these new tools and methods in the classroom. Virtual reality "represents a significant opportunity for students to enhance their visual thinking skills through the provision of rich visualizations in both physical and virtual environments" (Bermejo et al., 2023; Cevikbas et al., 2023). It also allows students to see how abstract concepts work in a three-dimensional environment, which facilitates their understanding and retention. In the case of 3D geometry, the use of NeoTrie VR (briefly Neotrie)[2] for learning mathematical geometrical concepts leads to better learning outcomes as shown by Rodríguez et al. (2021); see also Su et al. (2022) and Thomsen (2023) for a more recent exploration of the use of VR in mathematics education.

However, as remarked by Cevikbas et al. (2023), current classroom teachers find it complicated to implement virtual reality in the classroom, due to technological failures, cost, initial effort, health issues, and lack of awareness of AR/VR

1 https://www.vrs.org.uk/virtual-reality-applications/

2 http://www2.ual.es/neotrie

[see also Lai and Cheong (2022) and letter of concern[3]]. They are not sure of the effectiveness of the teaching and learning processes that are carried out with this new technology and, of course, they foresee the technical complications they will encounter. That is why it is necessary from educational institutions or companies specialized in education and ICT to facilitate real access to these new technologies, providing introductory courses and training.

Fernandez (2017) proposes a 12–15 months methodological process to aid the adoption of these technologies as basic elements within regular education. At that time, the high-quality VR devices available were HTC Vive, Windows Mixed Reality, Oculus Rift, etc., all requiring a gaming computer, at a high cost to schools. Moreover, this long process is intended to generate a limited and restricted solution to concrete learning experiences. It normally produces software with pre-set activities and challenges.

Totally immersive dynamical geometry environments, such us Neotrie, allows users to build their own mathematical activities in VR, although they normally require time and a good mathematical background to take full advantage of the software's capabilities.

Concerning the hardware, the Meta Quest[4] is the most affordable standalone (i.e., without a gaming computer) VR system for schools. However, for the proper functioning of a group activity or monitoring by the teacher one must view on an external screen what the player is doing in the game. In order to optimize this experience it is recommended using tablets to casting what the player is seeing. A router Wi-Fi 6 as well to expand the bandwidth (which schools do not normally have) to be able to transmit on non-gaming computers or tablets, via the website http://www.oculus.com/casting or the Meta app directly on the tablet. In some cases, the teachers have opted to use their own personal mobile phones (with unlimited data) to create a local Wi-Fi network, better than the one provided by the school. This technical part of equipment start-up and casting outages is still a waste of time that needs to be improved.

Based on the previous considerations, the following research question is posed:

*Is it possible for trainee teachers to produce appropriate activities in Neotrie, in a relatively short time?*

A standard Lewin's Action Research methodology (plan, act, observe, reflect) is being employed to investigate and apply the best possible introduction of VR and the use of Neotrie in the master's classroom to produce teaching material, adjusting to time and knowledge constraints (cf. Moral-Sánchez et al., 2022).

In Section 2, the software Neotrie is discussed briefly, including some references to research conducted to date and the new focus of this paper. Section 3 describes the pedagogical guidelines set in our university to plan the new intervention using Neotrie, as well as the assessment informed by the Technological, Pedagogical, and Content Knowledge (TPaCK) framework. The learning environment is then described in Section 4, explaining how the intervention is carried out. The objectives of the intervention are also given, allowing a clear organization of the work to be done by the pre-service teachers in small groups. In Section 5, the observation of our research is done mainly from the didactic sequences provided. On them, a system of objective data and parameters that help to score the sequences is established. As an example, one of the delivered sequences is resumed and analyzed in detail. This yields to draw some preliminary conclusions in Section 5.3. Finally, some discussions answering the posed question are in Section 6, including some adjustments to the implementation plan in subsequent iterations.

3 https://fairplayforkids.org/wp-content/uploads/2023/04/HorizonLetter.pdf

4 https://www.meta.com/

## 2 The virtual reality software Neotrie

Neotrie is a virtual reality software that enables users to create, interact, and manipulate geometrical objects. The available tools allow teachers to deal with many Geometry topics, especially three-dimensional ones, at educational levels ranging from primary school to first years of university. Some of these topics deal with graphs, polyhedra, tessellations, fractals, curves and surfaces, as well as their properties and transformations (see more details at https://www2.ual.es/neotrie/project-neotrie/).

The software has been developed in the video-game engine Unity by the spin-off Virtual Dor of the University of Almería since 2018, updating it to the high quality VR devices on the market over the last years, and more recently on the Meta Quest headsets. These constant updates produce unwanted bugs that appear in the testing in the classrooms, in the never-ending improvements and corrections.

Several studies in recent years show how the use of Neotrie strongly motivates students, develops and implements mathematical thinking in action, improves vision and geometric reasoning in space, stimulates cooperation and teamwork (see Rodríguez et al., 2021; Codina-Sánchez et al., 2022; Moral-Sánchez et al., 2022, 2023; Codina et al., 2023; Romero et al., 2023).

Until now, it was the researchers, doctoral students, and students of mathematics or master degree who mostly designed didactic sequences that were implemented in schools in an exploratory way. Thus, while doing so, data was taken to improve its design, correct the bugs found, and add new functions and tools to increase the scope of use, following a design-research study in cycles as in Collins et al. (2004) and Swan (2014).

On the other hand, the author has used Neotrie in his classes of linear geometry and also of algebraic topology in the Degree of Mathematics, as well as in the Master's Degree in Secondary Education Teaching of the University of Almería (Rodríguez, 2022a,b). In previous experiences, master's students were asked to build a particular figure (mosaic, polyhedron, fractal, ...), which they built manipulatively and also in virtual reality, along with some measurement calculations and study of its geometric or topological properties (Figure 1, left).

In the academic year 2022–23, the pre-service teachers were asked to design by themselves a didactic sequence using Neotrie and deliver it, in just 2 weeks without the possibility of testing it in real classes, or of being corrected or improved by the author, beyond small suggestions during its design. As a novelty, the students were able to use the first versions of the multiplayer mode, which helped them to learn from each other more quickly in the same VR scene (Figure 1, right).

FIGURE 1
**Left**: Master's students building mosaics with WMR headsets in 2019, complementing manipulative activities. **Right**: In 2023 working with Meta Quest in multiplayer mode in the same VR scene of Neotrie.

As remarked before, Neotrie has the flexibility for teachers to create their own activities. This makes it more difficult to use the software at the beginning, but it is worth the initial effort for teachers to propose their own activities, more varied than in other closer software. More details of this experience are provided in Section 4. In the next section, the pedagogical framework of our pilot experience is established, seeing how the freedom offered by Neotrie fits with the guidelines promoted by our university.

## 3 Pedagogical framework

Our pilot experience was framed in the subject "Practical Tools to develop the Mathematics Syllabus"[5] of the Master's Degree in Secondary Education Teaching taught at the University of Almería.

This master is informed by a constructivist pedagogical approach, emphasizing the active construction of knowledge by the pre-service teacher. Future teachers might learn how to design activities and learning environments that promote active student participation and the development of their critical thinking. In this way, a self-centered learning process is facilitated. For that, they must learn how to use technological tools to enhance instruction and student engagement. This includes pedagogical strategies and approaches adapted to the curriculum taught in secondary education, to the characteristics and needs of adolescents. They might be encouraged to reflect on their teaching, adjust their approaches based on student needs, and continue developing as educators throughout their careers. The Master's program also fosters collaboration among future teachers, as well as collaboration with other professionals in the educational field, such as parents, other teachers, and specialists.

In particular, in the subject "Practical Tools to develop the Mathematics Syllabus", they analyze the teacher's tasks in the mathematics classroom and search for and present materials and resources for teaching, establishing elements to study their function, their didactic interest, and selection criteria. At present, there is a wide range of materials and resources for teaching mathematics. Students are guided to be aware of these sources of classroom activity and to analyze them critically. They can see different methodologies for teaching mathematics, such as cooperative, problem-based and project-based learning. They use various ICT's and computer applications that facilitate the teaching and learning of mathematics (GeoGebra, Wolfram Alpha, Kahoot,...), as well as manipulative activities (polyhedra, tiling, fractals constructions,...).

This subject focuses on technological components, following the suggestions of Cevikbas et al. (2023) in a TPaCK framework, giving importance to mathematical software so that they know it, see its usefulness and ease of use to implement it in their future classes.

The "Technological, Pedagogical, and Content Knowledge (TPaCK) is built on Shulman's construct of Pedagogical Content Knowledge (PCK) to include technology knowledge as situated within content and pedagogical knowledge" (Shulman, 1986; Schmidt-Crawford et al., 2009).

Our assessment of the pre-service teachers' didactic sequences is based on the instrument designed by Schmidt-Crawford et al. (2009) to grade the TPaCK components. Adapted to the use of Neotrie this would be:

- Technological knowledge (TK): General use of Neotrie.
- Content knowledge (CK): Mathematical contents covered by Neotrie.
- Pedagogical knowledge (PK): Pedagogical instruments.
- Pedagogical content knowledge (PCK): Effective pedagogical instruments for teaching the mathematical contents.

5 https://www.ual.es/estudios/masteres/presentacion/plandeestudios/asignatura/7035/70352118

- Technological content knowledge (TCK): About the tools of Neotrie appropriate to display the mathematical contents.
- Technological pedagogical knowledge (TPK): How students can use the Neotrie tools to perform effectively the activities.
- Technological pedagogical content knowledge (TPCK): How the lesson is designed for learning the appropriate mathematical contents, using effective pedagogical instruments, with the help of Neotrie.

For the planning of our intervention and subsequent assessing of the didactic sequences, it has taken into account the initiative of the master's students and the peculiarity of Neotrie, and regroup the previous components in four items, giving more importance to the technological components:

1. Originality (TPCK): A learning situation is designed that is easier to carry out using virtual reality, or would be more complicated or tedious otherwise.
2. Mathematical content (PCK): It includes precise instructions, which guide the students in the realization of the tasks, with appropriate mathematical content that promotes a critical thinking.
3. Software mastery (TK, TPK): The guide is accompanied by a list of scaffolding tasks using the appropriate tools of Neotrie. It is important to know how the tools work and which ones to use to perform the tasks. This requires having tried to perform such tasks in order to predict the type of difficulties students will encounter.
4. Presentation (TK, TPK, PCK, TPCK): The pre-service teacher knows how to generate a didactic scene with texts, photos, and videos with the necessary instructions and geometric objects in the software to carry out the task. They also include a rubric with criteria for assessing the tasks.

## 4 Learning environment

The pilot experience in the subject "Practical Tools to Develop the Mathematics Syllabus" was carried out with a group of 32 pre-service teachers, 25 male and 17 female, mainly aged between 23 and 25 years. They were 21 mathematicians and 11 engineers (4 chemical, 3 civil, 3 computer, and 1 agriculture).

The all course was taught in 18 face-to-face sessions of 2,5 h (two per week), distributed from January to May 2023, with a trial intervention period in real classrooms in March.

Only the last two weeks of May (10 h) were dedicated to designing a didactic sequence using Neotrie in a room with computers with access to the internet and eight Meta Quest headsets. Of course, the sequences could not be tested in real classrooms, as the centers do not normally have VR glasses yet. And as we have indicated, this intervention serves as a first approach to the use of Neotrie, not to test it in real classrooms.

The objectives with these classes on Neotrie were the following:

1. Designing activities, based on real situations, that promote active student participation and critical thinking.
2. Exploring the use of VR to enhance teaching and student engagement.
3. Using VR to create content adapted to the curriculum taught in secondary education.
4. Working in small groups which promotes collaboration between future teachers.

Master's students were left free to organize the groups by themselves, manage their time, and way of working collaboratively.

In the first session, they grouped into eight small groups of 3–6 members. They visited the Neotrie website where they could find a guide to the software, including videos of how to use the tools,[6] and many examples of activities available on the community page.[7]

After this first contact with the software, each group chose a topic and shared it on the board with the rest of the class so that there would be no repetition.

They could consult the criteria and learning standards in the chosen geometric part of the Spanish secondary education curriculum and the most convenient level.

In the following sessions they worked in groups to organize the information, write the proposal in shared documents, and learn to handle the appropriate tools in Neotrie.

They were supported throughout this process, helping them with technical problems, guiding them in the use of Neotrie when necessary (although not much because they helped each other between groups), supervising the methodological proposals, the mathematical content and its assessment.

The four assessing criteria (Originality, Mathematical content, Mastery software, and Presentation) were proposed in general at the beginning of the intervention. Although, these were further refined after observing the work of some groups.

## 5 Results

Sequences delivered on the last day of the course are listed below (title and short description extracted from their texts). From these documents one can extract some strengths and weaknesses of our intervention.

The first consideration is that the mathematical content was in line with what is expected in the official curriculum. The most commonly chosen age was 13 years old and the sequences included a planning preferable for two sessions. The first session normally is devoted to learning the basics of Neotrie. The most used tools[8] were beginner ones (1, 2, 3, 4, 5, 8, 10, 11, 12, 13), but some groups also used experts ones (9, 16) and advanced ones (14, 15). This information was useful to assess the level of mastery.

Another aspect to take into account is if they have tried the tasks by themselves in Neotrie (indicated as *Checked*). This ensures the mastery of the software and at the same time they check the difficulties that the students would encounter. This is normally detected from the pictures of the activities performed.

6 https://www2.ual.es/neotrie/guia-2022

7 https://www2.ual.es/neotrie/comunidad

8 1. Basic hand actions; Create, face, edit, delete, move, grab, extrude; 2. Gallery of figures; 3. Photo camera; 4. Palette and pencil; 5. Tape; 6. Protractor; 7. Figure measures information; 8. Copy tool; 9. Scale copy tool; 10. Parallel tool; 11. Perpendicular tool; 12. Rotation tool; 13. Reflection tool; 14. Coordinate axis; 15. Labeling tool; 16. Sphere, cylinder, cone tool.

It should be noted that including a tool or an instruction in the sequence does not imply that it has actually been tested. Therefore, assessing software mastery is not straightforward and the author's observation during the lessons has been taken into account. In each case it is indicated whether the activity is based on a real situation. Some are inspired by a similar activity on the GeoGebra website.

1. Conics sections: the aim is to learn about the conic sections that can be obtained from a complete cone when it is cut by a plane using virtual reality. This is also worked on in GeoGebra. *Age*: 15; *Group size*: 3; *Sessions*: 2; *Tools*: 1, 2, 3, 4, 6, 12, 14, 16; *Checked*: Yes; *Real situation*: No (Geogebra).
2. 3D Puzzles: build a Tangram and a Soma cube in Neotrie, and propose to make different figures. They also use such figures to ask questions about areas and volumes. *Age*: 14; *Group size*: 3; *Sessions*: 3; *Tools*: 1, 3, 4, 5, 7, 8; *Checked*: Yes; *Real situation*: No.
3. Discovering the Koch Snowflake Fractal in 3D: the idea is to create and explore in 3D the Koch's Snowflake fractal, understanding its structure and properties. *Age*: 14; *Group size*: 3; *Sessions*: 2; *Tools*: 1, 2, 3, 8, 9,10, 12, 13; *Checked*: Yes; *Real situation*: No.
4. Creating your ideal house: in this activity, the students must make a plan of their house in 2D, with the Planner 5D program, with simple geometric figures such as squares, rectangles, triangles, circles, ... Then they are asked to build them in Neotrie with real concrete lengths or areas. *Age*: 13; *Group size*: 3; *Sessions*: 4; *Tools*: 1, 3, 5, 10, 11; *Checked*: No; *Real situation*: Yes.
5. Building a playground: the plan is to ask students to design and build in Neotrie a playground with some handrails and a swing. *Age*: 14; *Group size*: not-fixed; *Sessions*: 5; *Tools*: 1, 3, 4, 16; *Checked*: No; *Real situation*: Yes.
6. Pyramids of Giza: the objective is to represent in Neotrie the three pyramids of Giza on both small and real scales. *Age*: 13; *Group size*: 3-4; *Sessions*: 2; *Tools*: 1, 2, 3, 4, 5, 6, 7, 8, 9; *Checked*: No; *Real situation*: Yes.
7. The planetary system: In this proposal, students are asked to draw a series of spheres with certain sizes in Neotrie, color them, and place them at pre-established distances from each other, in order to build a scaled model of the planetary system. *Age*: 13; *Group size*: 3; *Sessions*: 2; *Tools*: 1, 3, 4, 8, 12, 14, 15; *Checked*: Yes; *Real situation*: No, GeoGebra.
8. Demonstrating remarkable identities with Neotrie: Students understand and internalize the remarkable identities of the square of a binomial and cube of a binomial through their geometric development both in the plane and in space in Neotrie. *Age*: 13; *Group size*: 3; *Sessions*: 3; *Tools*: 1, 4, 5, 9, 12, 16; *Checked*: Yes; *Real situation*: Yes.

The Table 1 takes into account the four criteria described in Section 3.

Next, the assessment process will be illustrated using a specific sequence that aligns with the four items, originality, mathematical content, software mastery and presentation, outlined in Section 3.

## 5.1 The pyramids of Giza

The following are the essential parts of the sequence Pyramids of Giza, by the group 6 (formed by one chemical engineer, one civil engineer and one mathematician), which will be analyzed in detail in the following section.

*"In this sequence, secondary students are asked to follow steps 1–5, accompanied by the pictures in Figure 2.*

*The objective is to recreate the three pyramids of Giza in Neotrie.*

*Steps to follow:*

1. *Basic actions and tools: Follow the guide of Neotrie to learn how to make the basic hand actions and how to use the tools to start working.*
2. *Insert a pyramid: Load from the gallery a pyramid with height 2 dm.*
3. *Duplicate objects: Make three copies of the pyramid with the copy tool.*
4. *Modify their color: red (Keops), blue (Kefren) and green (Micerinos).*
5. *Scale: Measure, modify, and scale the pyramids to get the them in real size.*

*In step 5, three tables in the colors red, blue, and green with the measures of the corresponding pyramids are given to the students: For the pyramid of Keops, height 146.6 m, side length 230.3 m, volume 2.592.350 $m^3$ and inclination 51°50'34"; for the pyramid of Kefren, height 143.9 m, side length 215.2 m, volume 2.211.096 $m^3$ and inclination 53°07'48"; and for the pyramid of Micerinos, height 66m, side length 103 m, volume 235.183 $m^3$ and inclination 51°20'00".*

In the didactic sequence, after the proposed task, some comments follow:

*Students have to use the tape to measure the proportions of the figures in Neotrie and compare them with those in the table. They realize that the ratio width/height is approximately the golden ratio, which they can calculate as approximately 3/2. Therefore, they must modify the pyramid to have a height 2 dm and base 3 dm.*

*Once the small pyramids have the correct measurements, the scale factor must be found: 73 for the pyramid of Keops, 72 for the pyramid of Kefren and 33 for the pyramid of Mycerinos.*

*The objectives sought fixed in this activity are to: Understand what a ratio is and how it relates to proportion; Understand how scale is used to represent objects or drawings in reduced or enlarged proportions; To learn how to scale geometric figures in three dimensions; Understand how the dimensions of a figure are changed by multiplying or dividing its measurements by a scale factor.*

*The curricular contents intended to be developed are the following: Concepts of ratio and proportion; concept of scale; use of scale to represent objects in reduced or enlarged proportions; and calculation of scaled dimensions using scale factors.*

*The use of the NeoTrie digital tool is intended to motivate students and develop their technological skills while achieving the aforementioned objectives and contents."*

TABLE 1 Assessment of the sequences over 20 points (each part is over 5).

| Group | Originality | Math. content | Software mastery | Presentation | Total |
|---|---|---|---|---|---|
| 1. Conics | 4 | 4 | 4 | 5 | 17 |
| 2. 3D puzzles | 4 | 3 | 4 | 4 | 15 |
| 3. Fractal | 4 | 4 | 3 | 3 | 14 |
| 4. House | 5 | 4 | 3 | 4 | 16 |
| 5. Playground | 5 | 4 | 2 | 3 | 14 |
| 6. Giza | 5 | 3 | 3 | 4 | 16 |
| 7. Identities | 4 | 4 | 4 | 4 | 16 |
| 8. Solar | 5 | 4 | 3 | 4 | 15 |
| Mean | 4.5 | 3.75 | 3.25 | 3.875 | 15.375 |

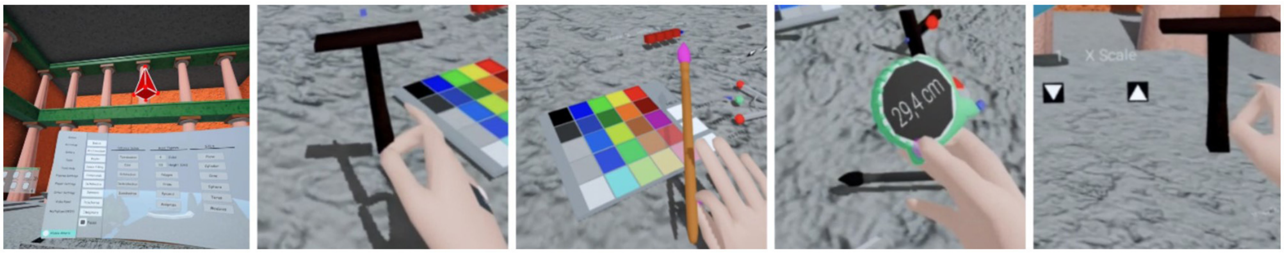


FIGURE 2
Pictures from the didactic sequence pyramids of Giza: gallery of figures, copy tool, palette and pencil, tape, and scale copy tool.

## 5.2 Analysis

We next provide some details for marking the sequence:

1. Originality (5 points): An ideal activity is proposed to be carried out in virtual reality, where the 3D figures can be modified and seen in real-time in a totally immersive environment.
2. Mathematical content (3 points): The instructions are precise and guide the students in the construction of the pyramids, encouraging them to think about how to modify the figures, and to look for the corresponding scale factor to obtain the real ones. However, although it is mentioned in the objectives, there are no questions to verify the changes in lengths, areas, and volumes when scaling the pyramid; There is no mention of the inclination, despite it being given to students as data.
3. Software mastery (3 points): The appropriate Neotrie tools to use for each step are listed. It is noted that they have been used and that they know the possible mistakes that could be made by the students. However, it would be necessary to indicate the restriction of movement in the axes, to obtain the small pyramid of height 2 dm and base 3 dm. It would also be missing other options to compare the area and volume measurements, or the use of the protractor to measure the inclination of the pyramids (see Figure 3).
4. Presentation (4 points): The trainee teachers did not generated a scene within Neotrie, not being necessary, as the proposal including pictures and instructions is sufficient to guide the student through the activity.

It is interesting to note at this point the software problem that appeared during the design of the activity: The ratio height/width of the Keops pyramid is equal to 146.6/230.3 = 0.635. Then pre-service teachers tried to load from the gallery of figures a pyramid of height 0.625 dm and size of the basis 1 dm. However, there was a software bug in the creation of the pyramid with a given height with decimal numbers. To solve this difficulty, they proposed step 2 which is more successful in that it forces the student to think in step 5 about how to modify the small pyramids to get the scaled real ones. We observe in this case, how thanks to a bug in the software, they have adapted and found an alternative way in the design of the task.

On the other hand, they made a mistake when calculating the change in scale. For the pyramid of Keops, 73 was calculated as 146.6 m/2 dm = 73.3, but it should be 1,466 dm/2 dm = 733. Perhaps they could have detected the error if they had made the pyramids in Neotrie, for being too small compared to the real one.

For the reader's interest, once the bug was solved, for a pyramid of base 1 dm and height 0.635 dm, the correct factor scale to get the Keops pyramid with real measures would be 230,3 m/1 dm = 2,303 dm/1 dm = 2,303. Some pictures following this alternative procedure are in Figure 4. It is appreciated how interesting it can be for students to build these pyramids in virtual reality with real sizes.

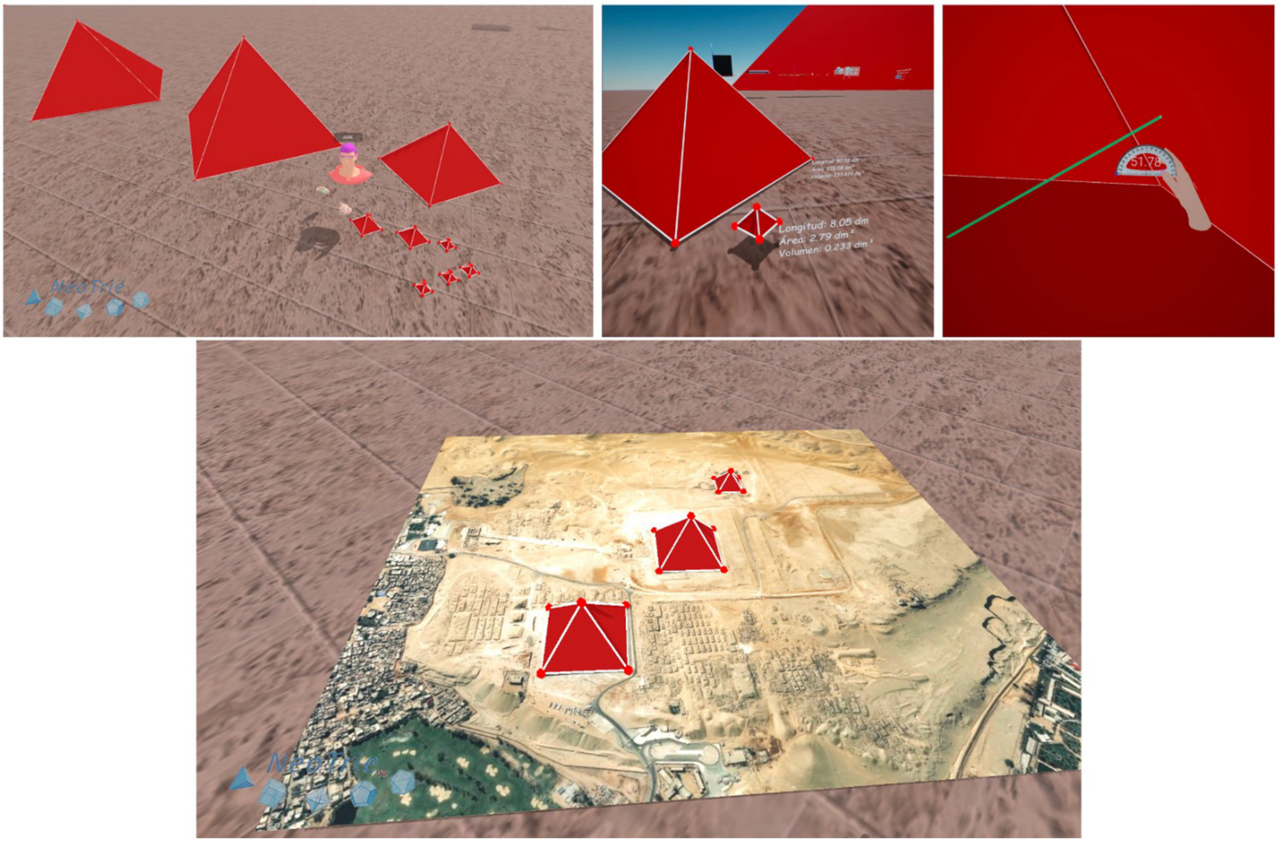


FIGURE 3
From left to right: Scales 1:10, and 1:1,000. Comparison of length, area and volume when scaling by 10. Measuring inclination 51.78°. Pyramids models on a satellite picture.

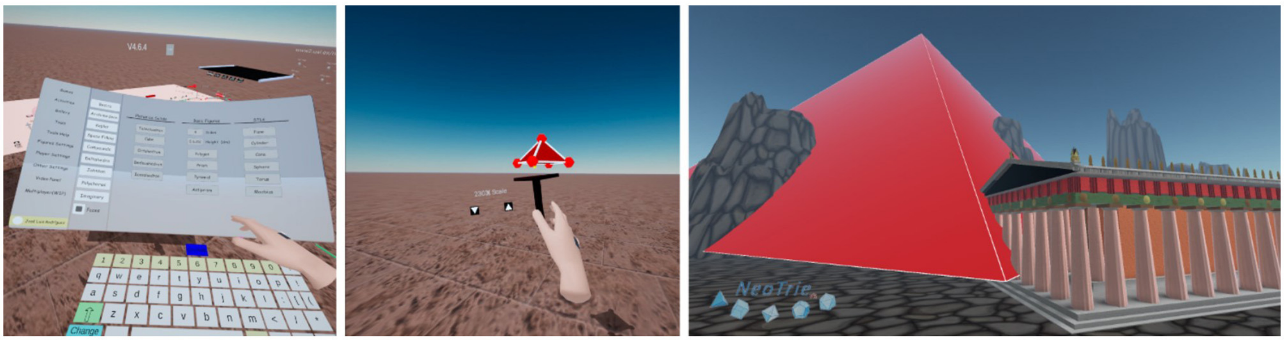

FIGURE 4
From left to right: Loading Keops pyramid with base size 1 dm and height 0.635 dm. Scale copy tool with factor 2,303. Real size of the Keops pyramid compared with the temple of Neotrie.

## 5.3 Preliminary conclusions

Our intervention allowed to accomplish the four objectives established in Section 4: (1) Pre-service teachers were able to design activities, many of them based on real situations, that promote active student participation and critical thinking, as they include scaffolding steps and interesting mathematical questions; (2) They have explored the use of VR and its potential to enhance the teaching and learning of geometry; (3) They have used VR to create content adapted to the secondary school curriculum; (4) Working in small groups has fostered their collaboration among pre-service teachers.

However, some drawbacks encountered should be overcome to achieve better training for our future teachers. The technical difficulties and software glitches slowed progress in designing sequences, although acceptable solutions and alternatives were found.

On the other hand, some groups would have needed more time to improve their use of Neotrie. Some of the sequences would have needed more time to be tested by themselves and revised. This would produce a better knowledge of the difficulties that secondary students would encounter in performing them.

It is worth highlighting some comments included in other delivered sequences. These reveal the awareness of the benefits that the use of Neotrie will generate in their future students: "This task allows to advance in spatial reasoning, previously imagining the resulting conic sections and subsequently checking the result, visualizing it in real time" (noted by Group 1); "Students can obtain abstract and complex concepts that are difficult to understand if taught in theoretical classes. [...] it captures students' attention as this software is quite innovative, and students learn through hands-on experience" (by Group 2); "Three-dimensional space offers a unique opportunity to explore mathematical concepts in an interactive and visually appealing way. Virtual reality and the active learning approach encourage the active participation of students, promoting creativity, problem solving and collaborative work" (by Group 3); "It is intended with this learning situation to improve the skills students' spatial and mathematical skills through a critical and appropriate use of technology. From the Neotrie application, a life situation will be exposed daily in which they will have to build elements of a park (handrails and swing) and they will have to justify the geometric figures with which they have carried out the model. Contributing exercises other than the usual ones and manipulative resources such as those exposed in this activity will allow students to generate motivation and interest in the knowledge that they intend to develop" (by Group 5); "Students can generate the geometric representation and also manipulate the different elements in an attractive and fun way" (by Group 7).

What they describe is their perception of how using Neotrie would turn out for their future students. Of course, testing of the sequences in real classrooms would be needed to obtain robust conclusions of these benefits.

## 6 Discussion

For the past years now, virtual reality has been changing rapidly both hardware and software, which keeps researchers and software developers busy, constantly forced to adapt to changes and avoid failures in the use of both software and hardware. These issues have affected the Neotrie team, which has had to adapt and work to bring their project activities to the classroom.

It was not until the academic year 2022–23 that we were able to conduct pre-service teacher sessions to test the effectiveness of using Neotrie to develop concrete classroom activities in a short time. In this situation, it was not clear how to grade a work of these characteristics in which part of it requires preparing the VR device and casting on computer or tablet, a training period on the use of the software, alignment with a pre-established curriculum, which does not yet take into account virtual reality, or if it does, it is very general within the use of new technologies. With recommendations proposed in the Technological Pedagogical Content Knowledge (TPACK) framework, pre-service teachers were given a rubric with four criteria to assess their sequences: Originality, Mathematical content, Mastery, and Presentation.

In just two weeks (four sessions of 2.5 h), pre-service teachers were able to overcome the mentioned difficulties and to create a fairly complete didactic sequence with Neotrie. The experience gained is good to start creating basic sequences. Pedagogical content learned in other subjects they have taken in the master's degree in teaching can be appreciated. However, the designed scenes can be improved as some groups have not made them themselves completely to realize all possible difficulties. We have shown some details of one of the sequences, "Pyramids of Giza", to see some limitations that are found when designing this type of sequences in a short time. It is also worth noting in general their belief in the benefits and motivation that VR would generate in their future students.

Therefore, answering the question established at the introduction: more training on Neotrie is needed so that pre-service teachers can introduce more mathematical content using more tools of the software, as well as testing by themselves the activities to detect possible difficulties in their future real classes.

Thus, in the next Master's course, 2 more weeks will be provided to learn how to use Neotrie, to ensure a more effective training. They will also be complemented with GeoGebra activities, approaching a more realistic situation in mathematics classrooms, as these usually have computers but not so many VR glasses. They will also have more time to do the mathematical part themselves and, in general, to complete the activities they ask their students to do, ensuring both the quality of the mathematical content and the mastery of Neotrie.

This type of sandbox software, like Neotrie, gives teachers a great deal of freedom and flexibility to create interesting VR scenes themselves, and even have the students themselves collaboratively generate them and then present them to their peers.

Our pilot experience can serve to help future teachers to use a new technological tool, such as Neotrie, so a final and validated didactic sequence is not expected for now, but it is clear that it serves to introduce them to an effective use of Neotrie in their classes.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

JR: Investigation, Methodology, Software, Visualization, Writing – original draft.

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## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Designing effective STEM courses: a mixed-methods study of the impact of a STEM education course on teachers' self-efficacy and course experiences

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Science, technology, engineering, and mathematics (STEM) fields play a critical role in the advancement of society and are expected to grow rapidly in the coming years. This study examines the development of a STEM education course and its impact on teachers' self-efficacy and course experiences. The study involves a mixed-methods approach, using survey and course assignment results gathered from 52 mathematics master's degree candidates who took an online STEM education course. Teachers' self-efficacy, STEM knowledge, reflections from reading materials, and lesson plans were quantitatively analyzed while content analyses was employed for the teachers' opinions on the role of each STEM subject and overall course evaluation. Results showed a significant increase in teachers' self-efficacy in teaching STEM subjects after completing the course. Additionally, teachers reported positive experiences related to course content, activities, and assignments. The study provides insights into the design and implementation of effective STEM courses and provides practical implications for designing operative STEM courses.

KEYWORDS
**STEM education, course development, self-efficacy, course experiences, Kazakhstan**

## Introduction

### Teacher self-efficacy and professional growth

Teacher self-efficacy refers to a teacher's belief in their ability to effect student outcomes through instructional practices (Bandura, 1997). Self-efficacy is not at a constant level throughout one's career and there are many factors that influence the increase or decrease of one's self-efficacy. A teacher's self-efficacy changes over time through a career peaking at approximately 23 years of experience and declining in later career stages (Klassen and Chiu, 2011). Day and Gu (2010) reported that a teacher's self-efficacy wanes and increases within a given school year depending on the expectations that are placed on a teacher during a specific time of year. Klassen and Chiu (2011) also found that one's social work environment and how one is perceived within a teaching or school community can both positively and negatively impact one's self-efficacy. Cooper and Carr (2019) noted that "low levels of teacher self-efficacy in teaching STEM-related disciplines is linked to poor teaching practices such as teacher-centred pedagogy, poor questioning and avoidance of teaching concepts considered too difficult" (p. 182). Ensuring that a teacher's self-efficacy is increased with respect to teaching science, technology, engineering, and mathematics (STEM) courses is imperative to improving the STEM experience for K-12 students.

To increase one's self-efficacy, a teacher might engage in enhancing their instructional strategies or increasing their content knowledge of a discipline. Ways that teachers choose to increase their professional and content knowledge through formal means like engaging in mandated or optional professional development programs or taking courses at a post-secondary institution or through informal means like self-directed learning or conversations with colleagues. Palmer (2011) found that cognitive mastery in understanding a concept was more impactful on a teacher's self-efficacy than past hands-on experience or enactive mastery. Avalos (2011) reviewed articles on teacher professional development and identified that both cognitive theories, including self-efficacy, and socio-cultural theory, including teaching context, play a role in teacher growth through a variety of forms of professional learning. In addition, Kayan-Fadlelmula et al. (2022) relates self-efficacy to positive outcome expectations and the achievement of those positive outcomes.

A conceptual model of teacher professional learning that worked to positively influence teacher self-efficacy was developed by Beauchamp et al. (2014). Their model included mastery experience, verbal persuasion, vicarious experience, and affective/physio states within a collaborative environment that works together to enhance teaching practice and, as a result, improve teacher self-efficacy. Beauchamp et al. (2014) found that "teacher efficacy was fostered by professional learning that allows teachers time to meet and talk, and spaces that promote conversation and collaboration" (p. 48). They recommended that professional development for teachers that increases one's self-efficacy be built around "sharing curriculum ideas and best practices, co-creating and sharing learning and teaching resources and learning new teaching strategies" (p. 59). Milner-Bolotin (2018) argued that "in order to change how students engage with STEM we have to change how we educate K-12 teachers and how we support them during their careers" (p. 2). Increasing teacher self-efficacy through professional development is of importance to STEM education as ensuring current teachers have the skill and knowledge to work in innovative ways to support student learning.

## STEM education

Science, technology, engineering, and mathematics education is a relatively new discipline in K-12 education and, as such, in pre-service education and in-service teacher professional development. As K-12 schools are implementing STEM programs and looking for teaching practices that integrate the fields of science, technology, engineering, and mathematics in multidisciplinary ways, "Educators at all levels are grappling with the complexities and issues that are emerging in what is a relatively new, and some might argue, ill-defined field" (Barkatsas et al., 2018, p. 93). With a call for a growing need for multi-disciplinary innovators in an increasingly global world, Barkatsas et al. (2018) recognized the need for current teachers to have support in the form of resources and knowledge to effectively implement STEM programs. Kayan-Fadlelmula et al. (2022) add that there is a need for teacher professional development programs that support one's efficacy and interest in teaching STEM. Mutseekwa (2021) proposes that practices such as field trips, work visits, and partnerships can facilitate increased collaboration among colleges, schools, professional scientists, and industry.

## STEM course development

The impact of various instructional strategies and course design features appears to differ. To facilitate the learning of course content in online STEM courses, designers should take into account a variety of instructional strategies and course design features. This may include fostering a learning community and providing opportunities for experienced students to impart their knowledge and share resources with their peers (Yang, 2017).

In order to develop a course to support the growth of teacher efficacy in teaching in a STEM context, courses at both the pre-service and in-service teacher levels were examined. In-service courses considered both courses offered at a master's level or orchestrated professional development experiences that were more than a one-time event. Though the designing of pre-service and in-service teacher education courses considers different characteristics of the audience and level of experience in a classroom or with a curriculum, both can offer insights into structures that can be identified as successful for different audiences (Nurbaeva et al., 2023).

Byrd et al. (2022) noted that, with respect to pre-service teachers, "meaningful experiences as a learner and an educator in integrated STEM methods courses" (p. 188) would lead to teachers that are more able to integrate standards from different disciplines and would lead to increased self-efficacy in planning and implementing STEM lessons. What constitutes a meaningful experience depends on the level of engagement of the students in the potential teaching of a STEM lesson to experiencing a STEM lesson as a student. Richmond et al. (2017) found that integrating "active learning strategies to model reform-based classroom practice" including "case studies and cooperative learning" (p. 20) activities that engage teachers in experiences that help them make sense of teaching in a way that potentially different than what they have been engaged in previously.

Beyond what was identified in the literature with respect to teacher professional development and self-efficacy, the context of STEM education poses an additional threat to a teachers' self-efficacy because the field is complex, multi-faceted, and ill-defined. Jong et al. (2021) noted that there is a need for teacher professional development in integrated and cross-disciplinary ways that support current teachers in developing their capacity beyond a singular discipline. Jong et al. (2021) identified that to build one's capacity in teaching, a professional development program should include the following elements "(a) content focus, (b) use of models and modelling, (c) active learning, (d) collaboration, (e) coaching and expert support, (f) feedback and reflection, and (g) sustained duration" (p. 81). Each of these elements serves to increase teachers' capacity for planning, teaching, and assessing in innovative ways that underlie STEM education.

## Experiences in STEM courses

Pre-service and in-service teacher experiences through engaging in courses designed to support the development of confidence and skills in teaching a STEM course have been explored in a variety of settings. In pre-service teacher education, Cooper and Carr (2019) found that pre-service teachers valued experiencing and learning more about disciplinary integration within and between the STEM fields and engaging in "authentic learning and inquiry-based pedagogies" (p. 180). Having elements of a course where participants fully experience the learning that happens through authentic experiences further supports future integration of those practices within one's context (Nielsen et al., 2019; Marynowski et al., 2021).

In-service teacher professional development also considers that the participants in the learning have professional experience that they draw on to position new learning within their experience of teaching. Rajbanshi et al. (2020) reported that in-service teacher educators need to be able to share their experiences alongside having opportunities to integrate new practices into their current context. Ensuring that there is both specific disciplinary content and pedagogy included for in-service teachers alongside opportunities for reflection about the implementation was noted by Nadelson et al. (2012). They stated that both content and pedagogy were important, however, teachers needed "time to think about STEM teaching and learning" (Nadelson et al., 2012, p. 166) so that they could develop a stronger sense of how to apply what they were learning.

One additional key component of experiences for both in-service and pre-service teachers was ensuring that the process of scientific inquiry (Nadelson et al., 2012) or the engineering design process (Shernoff et al., 2017) as a way to integrate seemingly separate disciplines in an integrated manner. As many teachers are trained in the pedagogy and/or in the content of separate disciplines, working in an integrated manner on potentially complex contexts or problems. Working in an integrated way on complex problems with in-service and pre-service teachers supports the later integration of disciplines in practice which is a goal of STEM education programs (Nadelson et al., 2012; Shernoff et al., 2017).

Several researchers have noted that there is a continued need to explore ways to enhance pre-service and in-service teacher professional development in unique knowledge and pedagogy in order to teach STEM in an integrated way (Teo and Ke, 2014; Milner-Bolotin, 2018; Margot and Kettler, 2019; Hill et al., 2020; Özer et al., 2020). The question that still remains is how can teachers be supported to improve their self-efficacy and knowledge of STEM education? There are many incentives for STEM education, but there are no effective courses to train teachers to provide this education. This study makes contribution to both literature and education as it investigates the effectiveness of a developed and implemented STEM course.

## Research purpose and research questions

One of the ways to design a new course is to look at teachers' perceptions and experiences which affect learning outcomes and satisfaction with a course. It is also essential to examine teachers' interest and feedback regarding the instructional strategies and course design features in new courses. This research investigated effective instructional approaches and course design elements in an online mathematics class provided to master's degree students. Teacher experiences in courses help in designing future courses and being able to identify what aspects of the course impacted knowledge, integration of STEM concepts, and self-efficacy (Nadelson et al., 2012; Rajbanshi et al., 2020; Abylkassymova et al., 2021).

The participants in this study were mathematics teachers who were teaching full-time, while enrolled in the online class. Their instruction experience and knowledge of teaching approaches let them give distinctive evaluations and comments associated with efficient teaching strategies and course design characteristics that contributed to their learning. Engaging in the course online is different from the other models of professional development for in-service teachers. In particular, the online context of the course was purposefully designed to ensure that the elements of effective teacher education were integrated. This research questions do not specifically attend to the fact that this course is online, however, this study serves to show that teacher self-efficacy, STEM content knowledge, and integration of STEM concepts into teaching can be improved through an online course.

The following research questions were identified for this study.

1. Are there any changes in the teachers' self-efficacy after participating in the course?
2. Are there changes in the participants' STEM education knowledge after participating in the course?
3. To what extent do mathematics teachers integrate STEM subjects into their lesson plans?
4. How do participants rate the role of each STEM subject?
5. What is the participants' overall evaluation of the course?

# Materials and methods

## Participants and context of the study

The study involved 52 mathematics teachers pursuing their master's degree at SDU University in Almaty, Kazakhstan. Among them, 13 (25%) were male, and 39 (75%) were female teachers. The participants had an average age of 26 and hailed from 12 different cities, with the majority (46%) originating from Almaty.

Their teaching assignments covered grades 1 through 12, with approximately half instructing at high schools and the other half at middle and elementary schools. As these individuals were teachers enrolled in the "STEM Education" course, the sampling method employed can be characterized as convenient sampling. The context of the study is a complete semester program on STEM education for master's degree students in mathematics (September–December 2022). This course comprised a 50-min lesson each week of theoretical lectures and two 50-min lessons per week of practical periods each. The course was taught online for teachers who were pursuing a master's degree in mathematics education at a Kazakhstan rural university. The course had no face-to-face meetings and was hosted in Webex (an online course management system).[1]

The theoretical part of the course covered an introduction to STEM education (2 weeks), integrated STEM education (1 week), gender differences in STEM (1 week), project-based learning (1 week), engineering design loop process (1 week), research and trends in STEM education (1 week), challenges in STEM education (1 week), STEM curriculum design (1 week), the role of each silo of STEM in STEM education (4 weeks), STEAM (science, technology, engineering, art, and mathematics) education (1 week). On the other hand, the practical part of the course focused on sharing STEM lesson plans and design challenges along with having quizzes and reflecting on reading materials.

The course was assessed across teachers' portfolios that consist of STEM lesson plans, design challenges, quizzes, participation, reflections on the reading materials, and presentation of produced works. Teachers filled in a pre- and a post-test survey respectively in the initial and the final week which investigated their STEM education knowledge and self-efficacy. All 52 teachers in the course gave their approval for this study.

## Instrument

The research questionnaire was designed to assess teachers' self-efficacy in STEM education. At the beginning of the questionnaire, the aims and background of the study were presented to the respondents. It was emphasized to the respondents that the research focus was on their views rather than on the specific content of the subject. The questionnaire was prepared using Socrative, an online assessment tool[2] and consisted of three sections, which included both open-ended and closed-ended questions assessed on a five-point Likert scale. The first part included demographic items (such as gender), and in the second section, the teachers demonstrated their self-efficacy in STEM education with 20 Likert items (such as *I am good at projects involving STEM*). The third section addressed teachers' knowledge about STEM education with four open-ended (such as *What is STEM Education?*) items (See **Appendix**). The Cronbach alpha coefficient was calculated as 0.804 and 0.860 respectively for pre-test and post-test scores on the second section of the questionnaire. Moreover, according to both pre-test and post-test scores, dropping none of the items increased the reliability coefficient. Along with standard Cronbach alpha coefficient we calculated the ordinal alpha coefficients for pre and posttests. They were calculated to be 0.86 for the posttest and 0.76 for the pretest, indicating high internal consistency in the ranking of responses for the posttest and slightly lower consistency for the pretest.

For the validity of the instrument, we sent it to two professors at SDU University for their views on the individual items. They evaluated the items in terms of relevance, clarity, and understandability. Depending on their feedback two items were revised and one item was dropped from the instrument.

## Design and procedure

This is the second time this course has been offered online. The first offering was for undergraduate students, and the third author adapted the course and is teaching the course to master's students for the first time. There were no prerequisites for this course, and the learning outcomes of the course were for participants: (1) develop scientific thinking strategies, (2) demonstrate basic knowledge in the fields of science, mathematics, and technology education, (3) utilize the vocabulary, primary concepts, definitions, and models applicable to STEM education, (4) develop innovative and alternative teaching methods and learning activities, and (5) analyze attributes, strengths, and weakness of current STEM education programs. These learning outcomes were measured informally at the beginning (pre-test) and at the end of the course (post-test) and formally through STEM lesson plans, STEM activities prepared by teachers, quizzes, participation and reflections from reading materials.

The main structure of the course design and the instructional strategies adopted were developed by the researchers based on the teacher professional development and STEM literature noted earlier. Instructional strategies included online discussion about the reading material, video demonstrations of design challenges, and discussion of STEM lesson plans. Teachers were awarded 10 points (around 6% of total grades) for participation in the online discussions. The reflection from reading materials asked teachers to summarize their understanding. Additionally, each teachers prepared four design challenges and four STEM lesson plans. Before preparing the design challenges and lesson plans, examples of these activities were presented to teachers. During the practice classes, teachers presented their lessons and design challenges with the instructor providing immediate feedback. The revised versions of both the design challenges and lesson plans, that is after the feedback, were uploaded to Moodle for prefinal and final grade evaluations. Participants provided MS Word documents for the lesson plans and YouTube links for the design challenges. The aim behind the YouTube videos was to have teachers use technology as an instructional strategy for the STEM course. No textbook was determined for the course and all reading materials were selected from journals indexed in SCOPUS. A summary of the designed course is presented in **Figure 1**.

## Data analysis

To evaluate teachers' self-efficacy, and knowledge before and after the course, a pre- and post-questionnaire was applied with

1 https://www.webex.com/
2 https://www.socrative.com/

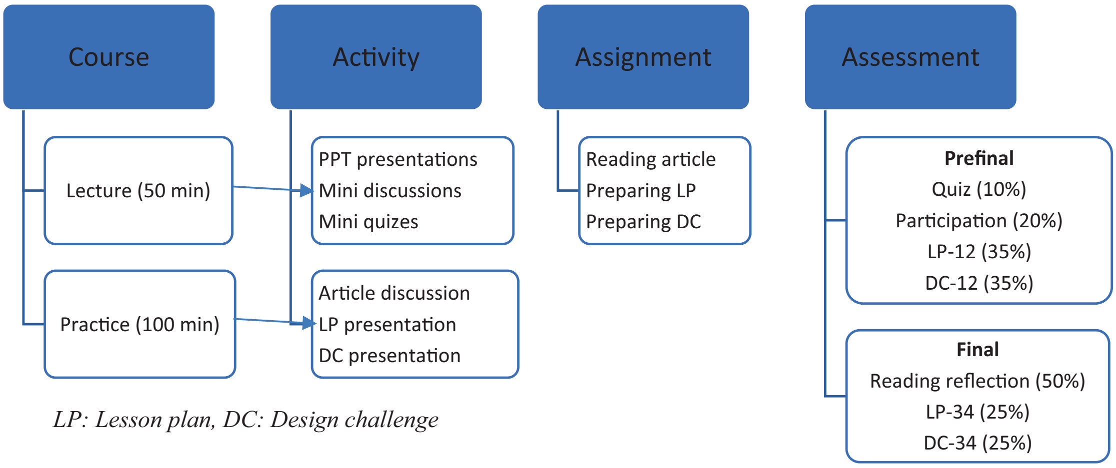


FIGURE 1
Science, technology, engineering, and mathematics course design.

a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Participants' demographic information was also collected from the administered survey. T-statistics were used to test the proposed hypotheses for the group differences such as pre-posttests. Wilcoxon W test was carried out to compare the scores from the first two and last two lesson plans.

Teachers were required to write reflections for each week's reading material. Each teacher's reflection ranged from one to two single-spaced pages. Except for the midterm and the final week, teachers were assigned reading articles. Each teacher provided 13 reflections. There were 52 teachers and a total of 615 reflections (61 reflections were not submitted). There was a rubric for the reading reflections which was composed of three sections; *summary of the reading* (70 points), *top three Take-Aways* (20 points), and *questions I still have* (10 points).

The rubric designed for evaluating the lesson plans developed by teachers were as follows: face validity and organization, that is the appearance of the lesson plan if it contains elements, such as date, aim, duration, school level, etc., of a standard lesson plan (10 points), objectives related to STEM education (20 points), description of the STEM activity (30 points), integration of the STEM subjects in the activity (20 points), assessment (10 points), and presentation (10 points). The first two lesson plans were prepared for the prefinal and were submitted for evaluation together, similarly, the last two lesson plans were submitted together and were graded for the final. That is why, we merged the scores from the first and second lesson plans and did the same for the third and fourth lesson plans. In other words, for each teacher, the average scores from the first two and last two lesson plans were compared for the effect of the course.

Similarly, design challenges were evaluated on the following bases: organization and quality (20 points), description of the activity (50 points), integration of the STEM subjects in the activity (20 points), and presentation (10 points). Regarding analyses of qualitative data, we utilized a content analysis, where views were categorized within teachers' responses to open-ended questions.

Data collected from quizzes, participation, reflections from reading materials and the design challenges were not analyzed in this study because they were beyond the research questions of the current study.

# Results

## Changes in teachers' self-efficacy

To respond to the first research question, that is, *are there any changes in the teachers' self-efficacy after participating in the course?* we used the results from the self-efficacy questionnaire. With the teachers responses, the following analyzes were performed.

A paired sample $t$-test (Table 1) was carried out to locate the difference between teachers' pre- and post-test scores about their self-efficacy in STEM education. The normality of the data was assessed by the Shapiro–Wilk test and a normal distribution was detected ($p > 0.05$).

The $t$-test indicated that teachers' post-test mean score (3.95) is significantly higher than the pre-test mean score (3.77). The means of pre and post-test scores are visualized in Figure 2.

## Changes in STEM education knowledge

For the second research question, teachers' STEM knowledge (second research question) was assessed through participant responses to the following open-ended questions on the questionnaire: *What is STEM? What is STEM Education? What is integrated STEM Education? What is STEAM?*

To see the effect of the STEM education course on teachers' STEM knowledge their initial and final (that is before the course and after the course) responses to these questions were compared.

TABLE 1 Paired sample $t$-test self-efficacy.

| | Statistic | df | $p$ | | Effect size |
|---|---|---|---|---|---|
| Student's $t$-test | −2.15 | 48 | 0.036 | Cohen's $d$ | −0.308 |

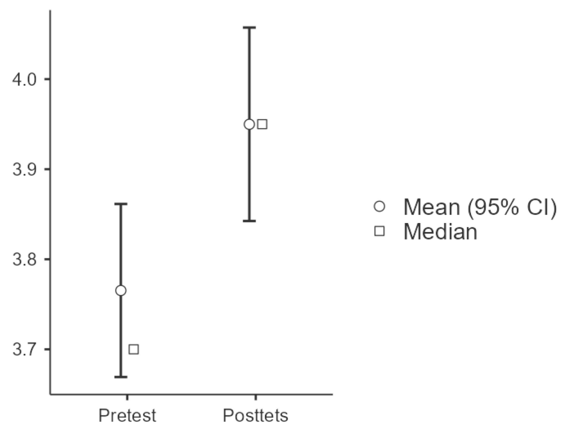

FIGURE 2
Pre-posttest means.

The comparisons were based on both the number of responses and a number of correct responses provided. Firstly, it was hypothesized that the more blank responses the more they do not know about STEM education. The number of teachers who responded to these four questions before the course was 46, 44, 27, and 29 respectively while after the course it was 47, 48, 46, and 47 respectively. This is visualized in Figure 3.

Teachers' responses (correct or incorrect) for the first two questions are almost the same while for the last two questions after the course they provided significantly more answers. The statistical significance test was done through the Chi-Square Goodness of Fit Test where for the third question $\chi^2 = 4.95$, $p = 0.026$, and the fourth question $\chi^2 = 4.26$, $p = 0.039$.

Secondly, it was hypothesized that the more correct responses the more they do have knowledge about STEM education. A number of correct responses for the items assessing teachers' knowledge about STEM education before and after the course are depicted in Figure 4.

Figure 4 indicates that the number of correct answers substantially increased after the course. The Chi-Square Test of Goodness of Fit was run to locate statistically significant differences. For *what is STEM* the statistics were calculated as $\chi^2 = 4.90$, $p = 0.027$, for *what is STEM Education* $\chi^2 = 1.65$, $p = 0.199$, for *what is integrated STEM Education* $\chi^2 = 10.40$, $p = 0.001$, and for *what is STEAM* $\chi^2 = 6.42$, $p = 0.011$. These statistics demonstrate that except for *what is STEM,* teachers' correct responses after the course are significantly higher than their initial responses.

## Integration of STEM subjects

To determine a response to the third research question (*To what extent do mathematics teachers integrate STEM subjects into their lesson plans?*) participants' lesson plans were examined. They prepared first and second lesson plans for the prefinal and third and fourth lessons plans for the final exam. We hypothesized that as the course progresses participants will prepare better STEM lesson plans. Lesson plans were examined on six variables; face validity and organization, objectives, STEM activity, integration of STEM subjects, assessment, and school level at which the lesson plans were prepared for.

There were 52 participants and from the first, second, third, and fourth lesson plans prepared by participants, we randomly selected 20 from each category (totally 80 lesson plans). The statistics such as the number of lesson plans examined, the mean of scores from each variable, and the standard deviation are presented in Table 2.

According to Figure 5, participants' first two and last two lesson plans seem to differ for integration of the STEM subjects, and school level while others such as face validity of the lesson plans remain similar. The statistically significant differences between the mean of the scores are tested through the Wilcoxon W test because our data indicated non-normal distribution.

Table 3 indicates that participants' first two and last two lesson plans were significantly different for the integration of STEM

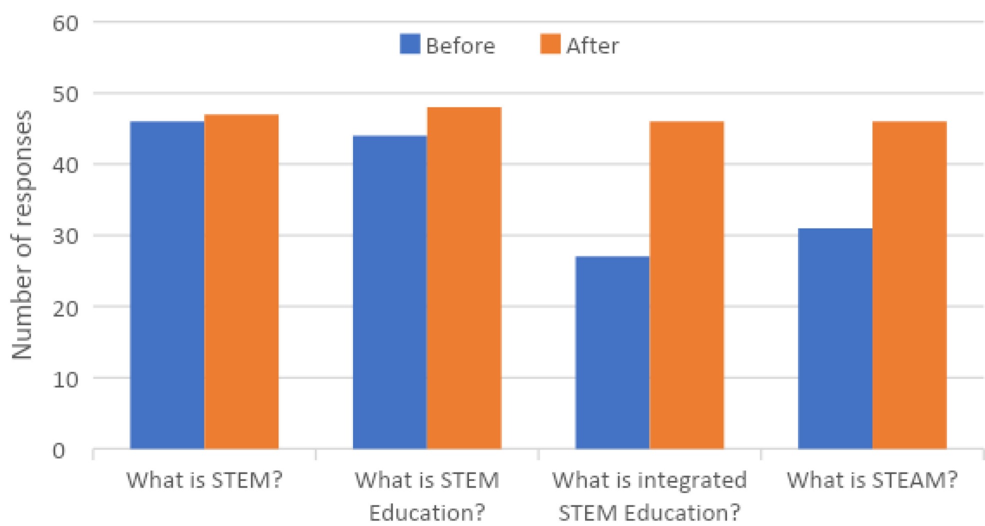

FIGURE 3
Number of responses to the knowledge items before and after the course.

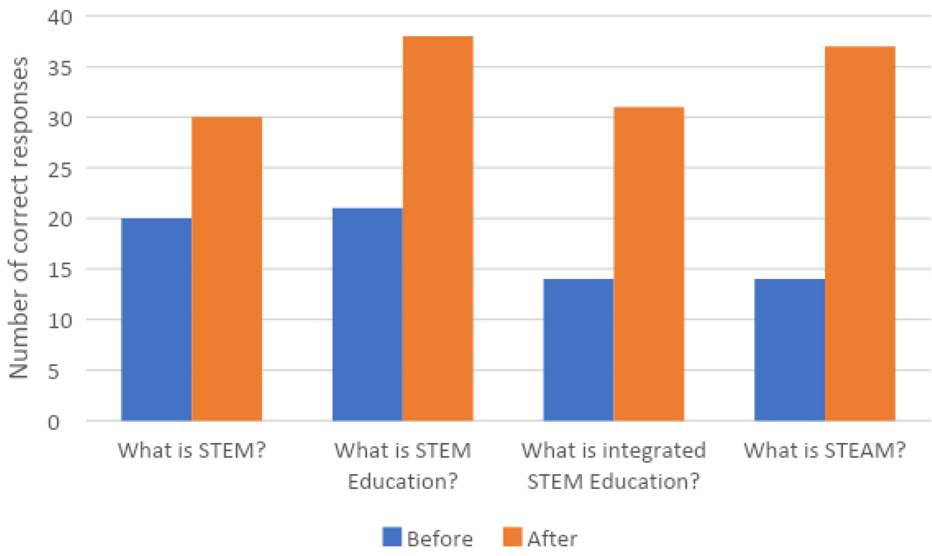


FIGURE 4
Number of correct responses before and after the course.

subjects and school level. In other words, the provided STEM education course has an effect on participants' integration of STEM subjects in their lesson plans ($p < 0.001$) and also has an effect on the school level for which they prepare the lesson plans for ($p = 0.005$). In other words, as the course progressed teachers prepared STEM lesson plans for higher grades. Which implies that they prepared more composite lesson plans.

## Rating the role of each STEM subject

At the end of the course, teachers were asked to rate (the fourth research question), from 5 to 1 where 5 corresponds to very important, the position of the role of each silo in integrated STEM education. A bar graph (Figure 6) with a stacked column was created to indicate this rating. This graph was created based on the responses from 43 teachers.

Figure 6 demonstrates that teachers rated the role of STEM silos as science, math, engineering, and technology from the most important to the least important. For instance, of the 43 teachers, 29 of them put science in the first place within STEM subjects, and 11, 1, 1, and 1 teachers put science in the second, third and fourth places, respectively. Similarly, math was inserted in the first place by 23 teachers and inserted in second, third and fourth places respectively by 10, 8, 2, and 0 teachers.

A supplementary question to rating the importance of each STEM subject was teachers' opinions on the role of each STEM subject in STEM education. Below some of the examples from teachers' views are presented. According to teachers' views, science is the foundation of STEM education. They stated that science provides the fundamental principles and concepts that students need to understand the natural world and how it works.

> Teacher 43: *Science is the most important element of STEM. Science asks questions about nature and gives answers in a fact-based and explanatory way. Science is mainly to promote students to design their works according to scientific principles, verify hypotheses based on evidence, and discover and come up with solutions to problems.*
> Teacher 8: *The main role of science in STEM education is to enable students to strengthen their education of scientific literacy and apply scientific knowledge, for example, in the subjects of physics, chemistry, and biological sciences.*

In pointing out the role of math, teachers emphasized the effect of math on critical thinking and its role in combining STEM subjects. Here is an example:

> Teacher 21: *I think the role of mathematics is important in STEM education because we necessarily use mathematical calculations when we make engineering models. Even if we use technology,*

TABLE 2 Statistics for lesson plans.

| | *N* | Mean | SD |
|---|---|---|---|
| Face validity-12 | 40 | 9.05 | 1.8 |
| Face validity-34 | 40 | 9.28 | 1.69 |
| Objectives-12 | 40 | 18.63 | 3.75 |
| Objectives-34 | 40 | 18.88 | 2.88 |
| STEM activity-12 | 40 | 26.75 | 4.88 |
| STEM activity-34 | 40 | 28.25 | 3.11 |
| Integration-12 | 40 | 9.38 | 3.04 |
| Integration-34 | 40 | 12.75 | 3.75 |
| Assessment-12 | 40 | 5.42 | 3.48 |
| Assessment-34 | 40 | 5.97 | 3.72 |
| School level-12 | 35 | 6.69 | 2.04 |
| School level-34 | 35 | 8.11 | 1.68 |

Twelve – first and second and 34 – third and fourth. The maximum points for each variable are 10, 20, 30, 20, and 10 points, respectively.

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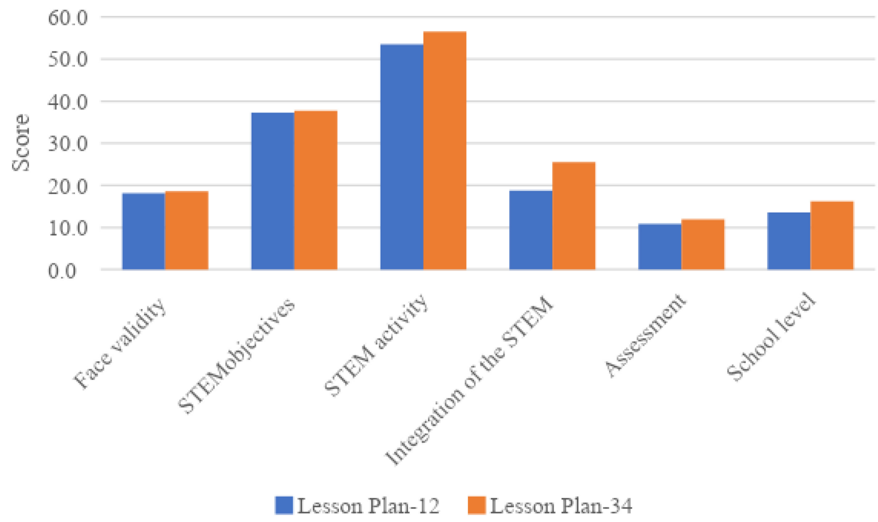


FIGURE 5
Comparison of first-second and third-fourth lesson plans.

*we cannot work with technology without building a mathematical model.*
Teacher 29: *Mathematics is a knowledge that can connect other subjects with each other. At the same time, mathematics increases the functional literacy of the student. Students can learn a variety of problem-solving techniques by solving various mathematical problems. We use mathematical concepts in both engineering and technology development. That is why it can be said that mathematics takes the first place in the STEM education system.*

Teachers pointed out the role of engineering in designing creative solutions and solving real-life problems. Following is an example which explains the role of technology.

Teacher 44: *Engineering plays an important role in STEM education and serves as a bridge between mathematics, technology, and science. Engineering tries to solve problems and applies mathematics, science and technology to design.*
Teacher 13: *In general, engineering not only increases our ability to solve problems but also helps us to look at the problem in a comprehensive way. In the process of solving the problem, critical thinking leads to increased interest in the work. It opens the way to strengthen inter-disciplinary communication and to look at each other from a new angle.*

TABLE 3 Wilcoxon *W* test for variables of the lessons plans.

| Pair 1 | Pair 2 | Statistic | *p* | Effect size |
|---|---|---|---|---|
| Face validity-12 | Face validity-34 | 30 | 0.5 | −0.2308 |
| Objectives-12 | Objectives-34 | 22 | 1 | −0.0222 |
| STEM activity-12 | STEM activity-34 | 49.5 | 0.108 | −0.4211 |
| Integration-12 | Integration-34 | 36 | **<0.001** | −0.8227 |
| Assessment-12 | Assessment-34 | 95 | 0.471 | −0.1775 |
| School level-12 | School level-34 | 96.5 | **0.005** | −0.5849 |

$H_a$ μ measure 1 – measure 2 ≠ 0, the effect size is the "Rank biserial correlation." Bold values indicate statistical significance.

Finally, teachers pointed out the role of technology in making stuff easier and affordable and saving time. The following example emphases the role of technology in providing good life conditions.

Teacher 2: *Nowadays, the use of technology is widespread due to the advanced age. That is, with the help of technology, we make the very difficult work easier. At the same time, the student's technological literacy will increase. Learning by using technology in life increases the free time of a person. Currently, technology is making the work that cannot be done by humans easier. STEM technology teaches students how to solve complex problems effectively and quickly. With the help of technology, the student's thinking ability develops, and the student also has the opportunity to invent new techniques. People can use technology to make things easier and easier. That is to say, we can use technology to make complex and difficult things easier, simpler and better to do.*

Over 4 weeks, teachers expressed their views regarding the role of one subject in STEM education per week. Since each week they provided responses for a different subject, they praised the role of each subject a lot. However, there was an agreement between writing their views and rating their views. In other words, the role of science was expressed explicitly and expressed a lot in agreement with the stacked graph in Figure 6.

## Overall evaluation of the course

At the end of the course, teachers were also asked what they liked and what they did not like in this course (fifth research question). In other words, they were asked to evaluate the course as a whole. Generally, teachers expressed positive feedback on the gains they received from the course.

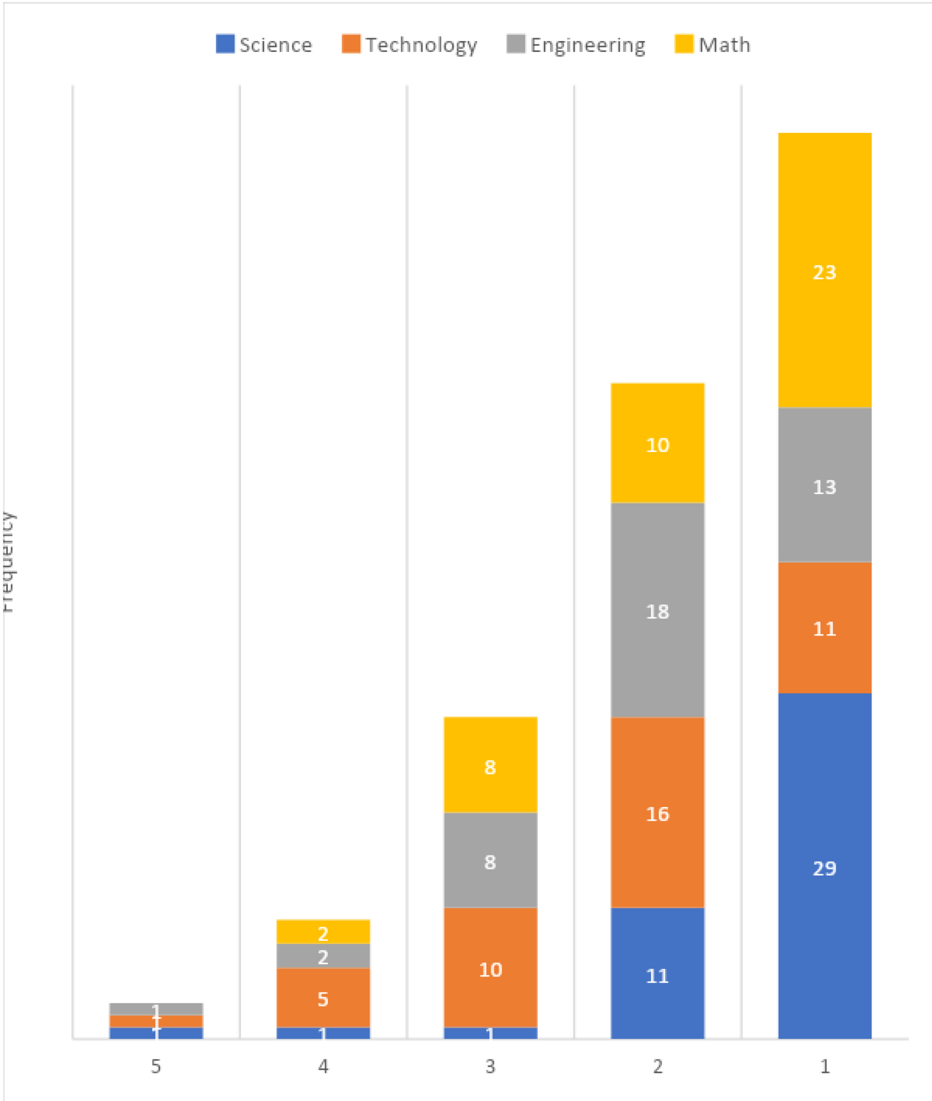


FIGURE 6
The role of each science, technology, engineering, and mathematics (STEM) subject within integrated STEM education.

An example of a totally positive view is as follows (Teacher 32): *I really liked this course because this course had a good impact on my experience. As a teacher, I realized that it is necessary to teach children not only the knowledge provided by the program but also to explain the use and benefits of these courses in life. I understood the relationship between mathematics with many directions. I have observed that it allows children to develop their thinking widely.*

An example of both negative and positive views together is as follows (Teacher 9): *I really like this course. I learn a lot about STEM, and I really excited to use it in future in my classes. Sometimes it was difficult for me to do design challenges. Cause, of the many ideas that I had, I couldn't realize them because of the tools that required. Many tools I couldn't afford. That's my DCs were so simple. I really liked Socrative from previous lessons, it helps us to review and repeat the topic. Thanks for everything. It was an amazing course.*

An example of a totally negative view is as follows (Teacher 18): I didn't like assessment methods. *I think it's too much for one person to make 4 lesson plans and 4 design challenges. And also, every week we wrote a quiz, and also every week we had to read an article and write a reflection. There are too many assignments, I think. Nothing I liked in this course. After this course, I have a negative attitude toward STEM.*

Many stated that it was useful and interesting and they will use STEM activities in their future classes. They also expressed that they learnt how to prepare STEM lesson plans. Besides, teachers complained about a high number of weekly assignments and difficulty in finding materials for developing STEM activities along with ideas about STEM activities.

## Discussion

This study examined the development and implementation of a STEM course designed to investigate effective instructional approaches and course design elements in an online mathematics class provided to master's degree students. The course focus and design responds to calls for the development of teacher efficacy in teaching STEM disciplines (Brown, 2012; Barkatsas et al., 2018; Kayan-Fadlelmula et al., 2022).

The online course design was deemed effective when it incorporated several key features, such as well-defined course objectives, appropriate alignment between objectives and assessments, consistent module structure, a range of assignments and learning activities, and a suitable balance between theoretical concepts and practical applications (Yang, 2017). Similarly, we incorporated STEM lesson plans, design challenges, quizzes, participation, reflections on the reading materials, and presentations to increase the effectiveness of the designed course. This is also consistent with what Huang et al. (2022) where they suggest to go beyond assessing teachers' attitudes and opinions and investigating their participation in STEM events by analyzing their online records of participation and interaction with colleagues, as well as examining the results of their work, such as lesson plans and projects.

Our study demonstrated that involvement in the STEM course substantially elevated the self-efficacy of teachers in teaching and creating STEM courses at the K-12 level. This finding was in parallel with Gardner et al.'s (2019) finding that teachers improved their self-efficacy and made productive changes in their classroom practices after participating in STEM professional development programs.

One of the aims of this course was to have teachers gain competencies in integrating STEM subjects. In the first two lesson plans participants generally integrated two subjects where math was one of the subjects usually. Of the 20 lesson plans we examined only three did not include math for the first and three for the second lesson plans. On the other hand, in the last two lesson plans they generally integrated three subjects where science was the most frequent. For instance, in the third lesson plan, only four did not include science while in the fourth only five did not include science. This finding is consistent with Jong et al. (2021) comment that teachers are not necessarily comfortable creating integrated opportunities for students to experience STEM as intended in a cross-disciplinary way and there is a need for teacher professional development which supports teacher planning in a wholistic way.

The effect of the course on teachers' STEM knowledge was also assessed. Four simple questions were asked before and after the course. We found that while teachers were familiar with the acronym STEM they were not able to differentiate between STEM, STEM education, and integrated STEM education before the course. Similarly, Teo and Ke (2014) noted that many pre-service teaches had an understanding of their individual discipline, but not the way STEM has been conceptualized and that there should be specialized programs or courses to support inservice teachers in STEM.

One of the most successful implementations in the course that effected teachers' learning products was that watching what their colleagues have prepared inspired them to produce better works, that is, lesson plans and design challenges. As expected, in their overall course evaluation teachers explicitly mentioned the effect of the video demonstrations by their peers on their own task developments. Designing, video recording, and uploading them to YouTube allowed teachers to develop their engineering design skills as well as their technology skills. Besides, preparing activities allowed a real-world application for the course and added value and meaning throughout the course work for the participants.

In their overall course evaluation teachers generally expressed positive views. According to Karpudewan et al. (2023), research supports the idea that knowledge and perceived effectiveness have a positive impact on STEM teaching.

An important part of the course time was devoted to discussing the reading materials assigned weekly. From the course evaluation data, the teachers indicated that the assignments were useful for their conceptualization of STEM. However, writing reflections on what they learnt from the reading materials did not seem enjoyable for them. This finding corroborates Mzoughi (2015) study who established that the majority of teachers did not find writing reflections from reading materials useful.

The participants in this study were mathematics teachers who were teaching full-time, while enrolled in the online class. Their instruction experience and knowledge of teaching approaches let them give distinctive evaluations and comments associated with efficient teaching strategies and course design characteristics that contributed to their learning.

Although our sample was mathematics teachers and mathematics is a fundamental subject surprisingly, they chose science to be the leading subject among the four silos of STEM. The explicit motive why teachers perceived science as the chief silo is that first, science compromises many subjects taught in schools, that is, physics, chemistry, astronomy, geology and biology, second our experience with the developed STEM lesson plans and activities indicate that it is easier to integrate other subjects into science. Moreover, STEM education is closely related to project-based learning (PBL) (Redmond et al., 2011) and asking a leading question such as *what is the effect of microwaves on different organs of the body* is the first step in PBL and the leading questions are usually science-based.

The teachers reported that the course was challenging but engaging, and they appreciated the use of real-world examples and hands-on activities to reinforce the course concepts. Despite the overall success of the course, because of heavy assignments, several teachers find it difficult and discouraging. These findings are consistent with the literature that highlights the importance of providing sufficient support and resources for teachers when implementing STEM education (Margot and Kettler, 2019).

The effect of the course is evident that as the course progressed the quality of the tasks prepared by teachers increased. In other words, the lesson plans and design challenges prepared as well as the quality of the reflections written from reading materials improved toward the end of the course. The findings suggest that a well-designed STEM course can improve teachers' self-efficacy, knowledge and experience providing STEM courses.

## Conclusion

This study delivers the findings of a semester-long STEM education course with 52 teachers pursuing master's degrees in mathematics. The study assessed participants' self-efficacy, STEM education knowledge, ability to integrate STEM subjects, rating the role of STEM subjects, and overall STEM course experiences. Pre- and post-test surveys and open-ended questions, STEM lesson plans, design challenges, and reading reflections were assessed to locate the effect of the course.

We showed participating in the STEM course significantly increased teachers' self-efficacy in teaching and designing STEM courses at the K-12 level. Moreover, our results convey the fact that the provided STEM education course has an effect on participants' STEM knowledge, and integration of STEM subjects in their lesson plans, and also has an effect on the quality of the developed STEM lesson plans. Furthermore, we demonstrated that teachers rated the role of science in STEM as the highest and that of technology as the least important. Finally, participants generally expressed that the STEM education course was useful and interesting and that they will use STEM activities in their future classes.

This study has specific limitations. The context was a single course over a full semester, the findings could be made more applicable to a broader context by including multiple courses and instructors in the analysis. In future research, it would be beneficial to explore the potential benefits of preparing lesson plans and design challenges and how they could motivate teachers in designing STEM lessons in schools.

A second limitation is that teachers video-recorded the design challenges that they prepared and they showed their work remotely. A face-to-face demonstration of the activities would be more effective in terms of understanding and engagement.

A third limitation is that the sample size was insufficient to evaluate nuanced group variations and potential interaction effects, such as those between females and males or advanced and novice participants. Future studies may see whether the suggested course design plays out in a parallel route for such subdivisions.

A fourth limitation of the study pertains to the quasi-experimental design employed, which lacked a control group, a factor that merits attention and acknowledgment. It is imperative to recognize that quasi-experimental designs without control groups inherently present challenges to internal validity. While such designs offer valuable perceptions into real-world settings, their limitations should be considered, as they may compromise the ability to draw causal inferences with a high degree of certainty. To enhance the robustness of future research, it is advisable to explore more intricate designs that incorporate control groups, thereby bolstering the internal validity and strengthening the overall methodological rigor of the investigation.

We suggest STEM teachers and course developers work with or at least discuss with researchers who have proficiency in teaching methods when electing and applying instructional approaches in STEM classes. The results presented in this article have already supported the proposed course design. That is why, we strongly recommend this design for those who seek to teach STEM education as a course at the tertiary level.

Our findings are expected to promote further research and development of STEM courses in the future. This study has found preparing lesson plans and designing STEM activities to be strong evidence of STEM course development. Overall, this study provides valuable insights into the development and implementation of effective STEM courses that can positively impact teachers' self-efficacy and experience in STEM fields.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

Ethical approval was not required for the studies involving humans because the participants were from corresponding authors' own class and the data were from instructors' own course notes, materials, and exams. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

## Author contributions

NZ: Data curation, Writing – original draft. ZY: Methodology, Writing – original draft. NB: Supervision, Writing – original draft. AA: Conceptualization, Writing – original draft. TB: Formal analysis, Writing – original draft. RM: Writing – original draft, Writing – review & editing.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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# Appendix

Instrument used in this study is as follows:

*A. Sociodemographic data*

Type of school you work at is private or public?
City you live in currently?
Grade levels you teach?

*B. Self-efficacy in STEM education*

We need science education for the future of our country.
We need mathematics education for the future of our country.
We need technology education for the future of our country.
We need engineering education for the future of our country.
I can prepare STEM lesson plans.
I like preparing STEM lesson plans.
I can create STEM activities.
I like creating STEM activities.
I can integrate math into science.
I can integrate math into technology.
I can integrate math into engineering.
I can integrate math into science, technology and engineering.
I like to read about STEM Education.
I am good at projects involving STEM.
I believe there is a need for STEM Education.
I care about developments in STEM Education.
I would like more/advanced courses in STEM Education.
I intend to further develop my abilities in STEM Education.
STEM activities increases creativity.
STEM activities increases critical thinking.

*C. Open-ended questions*

What is STEM?
What is STEM Education?
What is integrated STEM Education?
What is STEAM?

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# Enhancing digital literacy in primary education through augmented reality

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Currently, there is a need to develop digital competencies already because they are included in the new curriculum. This article explores the field of augmented reality (AR) and its educational potential to bolster digital literacy in primary education. The core objective is to scrutinize the suitable use of AR-integrated mobile applications in primary schooling, spotlighting widely adopted apps and their practical applications. The article underscores digital literacy as a key competence for children's self-directed future learning. In our research we used a combination of qualitative and quantitative research approaches. It seeks to identify the impacts and benefits of AR in primary school settings. In a natural didactic context, it is conducted as action research. The methodology includes direct observation of pupils engaging with the AR app Quiver during educational tasks, complemented by discussions with their teacher as a focus group. Additionally, the study gathers insights from parents via questionnaires based on their perceptions of AR in education. The analysis of the interview data utilizes the open coding technique to interpret the findings. The relevance of the research was confirmed by the consistency of results when transitioning from onsite to online learning environments. The study showed that AR engagement helped to increase the digital literacy of the participating pupils, showing high levels of engagement, motivation and collaborative communication.

KEYWORDS

**Quiver applications, AR in primary education, focus group, observation, Platonic solids, digital literacy**

## 1 Introduction

In today's dynamic educational sphere, ICT technologies are not just present but pivotal in shaping the everyday learning journey of young minds in pre-primary and primary school settings (Sujansky and Ferri-Reed, 2009). These cutting-edge technological strides open a treasure trove of possibilities for educators, revolutionizing traditional teaching methodologies. Amidst an evolving educational world, there's a critical and growing demand for STEAM (Science, Technology, Engineering, Art and Mathematics) education at all levels, fueled by the burgeoning market need for skilled professionals in these sectors (Berger-Haladová and Ferko, 2019). This article takes a dive into how we can make STEAM irresistible to the tech-savvy Generation Z and Alpha, starting right from their first ABCs. It's about reimagining education through innovative, engaging, and downright captivating methods. And at the forefront of this educational renaissance Augmented Reality (AR). This article explores if AR is truly not just a technological trend, but a kind of game-changer in the realm of education, promising to transform how we teach, learn, and inspire the innovators of tomorrow.

We were interested in how students would respond to using the Quiver app in math lessons given that students often struggle with imagination.

## 2 Digital competence

Nowadays, it is desirable to develop digital competences in pupils as early as the 1st grade of elementary schools, which is also confirmed by the inclusion of these competences in the framework educational program. We believe that using AR apps develops these competencies. Many authors have defined the concept of competence. According to Chvála and Strakova (2014), one of the possible definitions is the designation of competence as the application of what we know and can do as a task or problem in everyday life. Key competencies are competences that represent the sum of knowledge, skills, and abilities important for the student's personal development and their application in society.

Different teaching methods can be used to develop pupils' IT thinking. Through the use of ICT –mediated instruction students can develop higher-order thinking skills. Critical thinking is an intellectual process that questions information and examines facts. Barak and Dori (2009) also pointed out that critical thinking is a skill that requires the ability to think independently, clearly, reflectively, logically and rationally in an effort to take responsibility and to control one's own mind. Categorization and classification is one of the higher-order skills which can be developed through the use of ICT—mediated instruction. Methods that can be applied to pupils in the primary school with the aim to achieve more effective learning, a deeper and more permanent knowledge of the issue and to motivate pupils to learn and think are active learning through pupil's own activity, discussions, solutions problems, critical thinking, E-U-R, group teaching, evaluation, learning in the form of a game and more. E-U-R is one of the teaching planning methods that is built on a constructivist approach to learning. Sometimes this model is also called the three-phase model of learning. It contains the initial letters of these words: evocation, awareness of the meaning of information and reflection (Novotný et al., 2001).

For pupils in primary school, it is appropriate to rely on their experiences when learning, and thus develop their IT concepts through their own activity and provide them with a better grasp and mastery of the given topics. At the method of solving problems based on trial and error, students try to come up with different solutions; a mistake is perceived here positively and naturally, when pupils learn through it. The basis of IT thinking should be the active work of the pupil, when creative thinking, self-confidence, joy, and success in learning. The discussion method supports the pupils' communication skills and self-confidence, pupils can react to each other and learn to formulate their opinions and arguments (Institute of Medicine and National Research Council, 2015).

## 3 Augmented reality

As previously mentioned, this paper delves into the innovative use of Augmented Reality (AR) in primary education, a crucial STEAM area, with a specific focus on its perception by future primary teachers. It is also called immersive technology.

AR technology revolutionizes students' or pupils' access to educational content, transcending geographical and temporal barriers to create a flexible, mobile learning environment (Ganguly, 2010). This approach can be aligned with the constructivist theory of learning, which posits that knowledge is actively constructed through personal experiences and interactions within a socio-cultural context (Tóthová et al., 2017; McDowall, 2016). Each tool can be used for different teaching methods from classical to constructivist teaching. The body of research explores various theories and practical applications of AR in education, presenting a spectrum of solutions and analyses (e.g., Azuma, 1997).

The visual impact of AR is particularly significant for young learners, where motivation plays a pivotal role (Berger-Haladová and Ferko, 2019). For example, AR can transform the teaching of complex subjects like geometry into an engaging experience, as demonstrated by apps such as Quiver *3D Augmented Reality coloring apps* (where colored images come to life in the learning space). The visual and interactive elements of AR can help children remember information better and understand subjects more easily. AR can foster creative thinking and innovation by providing space for pupils to experiment, create and explore new possibilities. The use of AR can motivate students to learn and enhance their participation and engagement during lessons (Prodromou, 2020).

The positive impacts of AR in educational settings are well-supported in literature. AR allows the coexistence of virtual objects and real environments, enabling learners to comprehend complex spatial relationships and abstract concepts at the same time (Arvanitis et al., 2007). Radu (2014) emphasizes AR's benefits in enhancing students' understanding, memory retention, collaboration, and motivation.

When integrated into educational environments, AR applications can:

- Engage students in authentic explorations in the real world.
- Facilitate the observation of phenomena that are otherwise challenging to perceive with the naked eye, by juxtaposing virtual elements with real objects.
- Boost student motivation and foster the development of advanced investigative skills.
- Create immersive hybrid learning environments, blending digital and physical elements, which are instrumental in developing comprehensive processing skills (Niraj, 2023).

The article was created during the time of COVID when students were at home. At this time, they needed a more tangible understanding of what they were learning. That's why we used AR applications. Here is a brief overview of the most popular AR applications, which helped us to choose the most suitable application for our research. We assessed the suitability of mobile applications integrated with augmented reality in primary education and their practical use (Korenova et al., 2019).

- Quiver: This app merges traditional coloring with advanced AR technology. Featuring the Platonic Solids. It enables students to visualize three-dimensional shapes, enhancing their understanding of geometry in a fun, interactive way. Beyond mathematics, Quiver's diverse printable worksheets make it suitable also for teaching natural sciences under the STEAM concept.

- Quiver Education: Tailored for pre-primary and lower primary education, this coloring app includes a variety of educational materials such as descriptions of erupting volcanoes, world capitals, and cellular structures.
- Halo AR: This application brings books to life. After reading, students use Halo AR to uncover questions and tasks hidden on the book cover, fostering independence and motivation through interactive learning.
- Catchy: This app creates a secret letter puzzle in the classroom. Students gather letters during the class and assemble them to solve the puzzle. It is suitable for example for language lessons (both Czech and English).
- AR Makr: Teachers can create spatial stories or fairy tales, which pupils can then for example narrate or demonstrate to their classmates, enhancing storytelling skills.
- AR Flashcards Shapes and Addition: The AR Flashcards are available at no cost, featuring Shapes and Addition as premium, paid modules. Despite their associated fee, the value derived from these modules makes them a worthy investment. This suite of applications is specifically designed to foster the development of basic mathematical skills in children. The Addition module employs captivating animal imagery to effectively illustrate the concept of counting, spanning equations from $0+1$ to $9+9$. The Shapes module, on the other hand, allows students to interactively color various geometric figures, while simultaneously learning their names, colors, and forms in English. Importantly, it also offers insights into the real-world applications and occurrences of these shapes. Overall, this application serves as a suitable resource for mathematics education.
- Augmented Polyhedrons—Mirage: This app aids in teaching mathematics by allowing students to compare three-dimensional shapes side-by-side.
- ARuler: A practical tool for measuring real-world objects in various units, enhancing the learning experience in mathematics and science.

In the realm of natural science, AR apps bring abstract concepts to life, such as human anatomy and the universe:

- Night Sky: Ideal for teaching about constellations, allowing students to view real constellations in their actual positions.
- Spacecraft 3D: This app has been developed in collaboration with NASA, this app showcases various space technologies, enriching lessons about Mars, Earth, and the universe.

Additional applications suitable for both pre-primary and primary education stimulate imagination and aid in various subjects:

- AR Flashcards: The application proves to be a useful tool for post-printing online, e.g., online worksheets, facilitating the practice and reinforcement of English animal vocabulary as well as the English alphabet.
- Aurasma (HP Reveal): This innovative app enables students to create images or videos with ease. Educators can embed assignments within the classroom by uploading specific content, or by directing the camera at a title, students can associate it with, e.g., an image. Aurasma is versatile and can be integrated across various subjects.It also encourages creativity by allowing students to create pictures or videos, with tasks hidden in the classroom.
- AR Dragon: Designed for children, including also those in pre-primary education, AR Dragon is an engaging application that simulates pet care. Through interactive play, it nurtures a sense of responsibility and fosters the development of social competencies.
- Sketch AR: This is an AI based mobile app allowing anyone to draw. Theory and practice are effectively combined into fun experiences.
- Animal 4D+: With Animal 4D+, students can marvel at three-dimensional animals projected right onto their desks. The application not only visualizes the animals but also includes sounds, providing a multi-sensory experience of wildlife that students may have never encountered.
- Catchy: Catchy reveals a hidden puzzle comprised of letters that students collect and arrange to solve. This interactive learning tool is useful for both Czech and English language instruction.
- AR Makr: AR Makr empowers educators to create spatial narratives or fairy tales. Subsequently, students can narrate or visually share these stories with their peers, enhancing both storytelling and presentation skills.

# 4 Materials and methods

## 4.1 Research design

The objective of this article is to investigate the dynamics between augmented reality (AR) and children within the context of primary education, both online and in face-to-face classroom settings.

### 4.1.1 Applications suitable for primary school level

In the academic year 2019/2020, a series of AR applications were tested in primary education, both in school and in online learning. This exploration led to the identification of several AR apps suited to primary school settings.

After reviewing the available AR applications suitable for 1st grade of elementary school that meet STEAM requirements, we decided to include the Quiver application for teaching Platonic solids. This application covers the topic of Platonic solids very comprehensively and it is visually appealing to pupils (RVP, 2016).

### 4.1.2 Research sample: third-grade pupils and their parents

Pupils worked with the Quiver application both in groups during face-to-face class and individually during online sessions due to the COVID pandemic. Initially, they were unaware of the specific learning outcomes anticipated from the application. Provided with paper printouts of Platonic solids (online learners viewed these on their screens), they collaboratively discerned the nature of the bodies and their constituent geometries. Pupils working online independently, similarly deduced the represented element. The application was then utilized for approximately 20 min, with each group exploring a distinct worksheet, discussing, and interpreting the information related to Platonic bodies. Subsequently, groups prepared presentations of their observations. A comparative analysis followed, wherein pupils deliberated over the similarities and discrepancies of their findings, deepening their comprehension of the facets and configurations of the solids.

### 4.1.3 Research questions

How did the pupils react to the first use of the Quiver application on the topic of Platonic solids?

What were the initial impressions of parents regarding the use of the Quiver application in their child's education on Platonic solids?

#### 4.1.3.1 Hypothesis (qualitative research)

According to pupils and parental feedback, the Quiver application boosts pupils' interest in discovering properties of Platonic solids.

#### 4.1.3.2 Hypothesis (quantitative research)

The Quiver application helps pupils discover the properties of Platonic solids and visualize them in 2D.

#### 4.1.3.3 Methodological approach

This study adopts a mixed-methods approach, employing both qualitative and quantitative research techniques.

Qualitative Research: Standard Focus groups consisting of 6–8 randomly selected children the scope of the teaching unit was up to 2 h. The teacher then leads a discussion, asking the children questions. Focus groups were conducted to capture in-depth insights during both online and face-to-face sessions. We utilized the Quiver application as part of a novel Mathematics curriculum. We observed the pupils' reactions on the use of Quiver application while learning about Platonic solids. These observations were then cross-compared for a comprehensive understanding (Švaříček and Šedová, 2007).

Quantitative Research: A structured questionnaire was administered to gauge the perceptions of parents towards the usage of Quiver application during online learning. At the beginning of the lesson on Platonic solids, the pupils were divided into two groups. During the introduction to Platonic solids and the exploration of their properties, the first group used the Quiver application, while the second group had only educational cards (link). Afterwards, the pupils were tasked with completing a worksheet (without using the Quiver application or the cards) based on the knowledge they had gained during the preparation time.

The class was divided into 2 parts. One group had the Quiver app and a worksheet, the other group had just a printed image. The pupils were also divided into study groups of three. Each group had a different Platonic solid.

The qualitative phase involved focus groups coupled with observation.

The quantitative phase involved questionnaires for parents who assisted their children with the Quiver application throughout the online educational process.

For practical implementation, the focus group was integrated into an action research framework with students. After the final analysis of the options/benefits listed in the overview, we chose the Quiver application. This method was expected to promote openness and facilitate the sharing of views.

The characteristics of quality action research were defined as follows:

- Pupils reflect and improve practice in their natural environment.
- The experience gained is shared with the participants, but also with everyone else.
- Data are collected by the research participants themselves and their questions are addressed.
- Cooperation of all participants in all phases of research.
- Differences in the status of individual participants are put aside.
- Cooperation between all participants works and the community can critically evaluate the situation.
- Children are ready for self-reflection, self-evaluation and self-management, there is effective (and collaborative) learning through mistakes.
- The idea that everyone is their own best teacher is encouraged (Zuber-Skerrit and Fletcher, 2007, p. 415).

## 5 Results

### 5.1 Execution of research

The research was conducted at the Elementary School and Kindergarten in Ludgeřovice, where I have been teaching pupils aged 7 to 12 for 6 years. Our pedagogical approach primarily utilizes technology to reinforce existing curriculum frameworks and to stimulate pupil engagement and motivation while booting new curriculum. The school is equipped with 120 iPads, as well as Dash and Dot robots, Ozobots, Lego Mindstorms, Beebots, and Micro:bits, all of which are integrated into classroom activities as per the teachers' discretion. There is also a classroom equipped with iPads and robots which we use mainly for more digitally advanced work or for more sophisticated projects involving these devices and robots.

From kindergarten through to the lower primary education (1st and 2nd grades), we commence programming activities with Bee-bots called "robotic bees," which boast an intuitive and straightforward design. Progressing to the 3rd and 4th grades, pupils advance to programming Ozobots, which can be controlled via color-coded commands or through a programming language on a PC or iPad. In the 3rd grade, we introduced the simpler applications of Dash and Dot robots, progressing to more complex code-building in the programming language with older pupils in the 4th and 5th grades. iPads are employed from the first grade onwards, with each classroom providing a one-to-one ratio of devices to pupils.

This school's technological provision is exceptional; the majority of schools in the Czech Republic do not possess such resources, nor are the teachers typically trained to utilize them effectively. Nonetheless, the Ministry of Education has mandated the inclusion of these competencies in the educational curriculum, necessitating that schools adapt to these requisites within 2 years.

During the academic year 2021–2022, our study was carried out among third-grade pupils at this elementary school, both in face-to-face and online sessions necessitated by the COVID-19 pandemic. There were 26 pupils in the first class and 24 pupils in the second class. The pupils were already acquainted with iPads and could control them pretty well. Our research entailed observing pupils' behavior while using the Quiver application, particularly as they engaged with a new curriculum segment on solids.

The application proved instrumental in enabling pupils to visualize mathematical concepts and other abstract notions. In

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conclusion, two reflective questions were posed by the educator (Figure 1):

What knowledge did you acquire that was new to you?

Did you find this educational activity enjoyable?

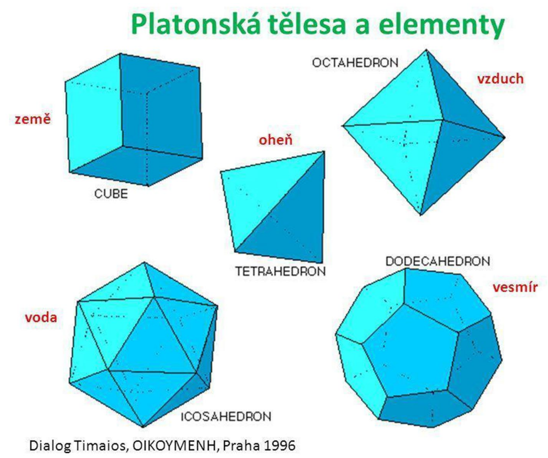


FIGURE 1
Platonic solids received by pupils.

## 5.2 Qualitative method: observation

The objective of the unstructured observation (without a pre-prepared scheme) was to record the pedagogical process wherein the educator deliberately facilitated the social constructivist approach to fostering the child's intrinsic motivation via augmented reality (AR). The observations were audio-recorded and subsequently transcribed for analysis. Through the implementation of qualitative research via observation, we garnered the following insights.

## 5.3 Focus group elaboration

The focus group was employed as a primary method for data collection. Defined as a collective discussion format, the focus group facilitates dynamic interaction among participants, in this case, enabling students to articulate their opinions and elucidate their perspectives freely. The primary methodological approach of qualitative research was unstructured observation, where the observer's interaction with the participants was minimized to avoid influencing their natural behavior. This observational stance allowed for the assessment of cooperation, creativity, motivation, digital literacy, and independent learning as mediated through augmented reality. Observations were categorized as either direct, which involved monitoring the communication between students, or indirect, capturing authentic interactions within the educational process.

FIGURE 2
Pupils' work with the Quiver app.

## 5.4 Research implementation

For practical implementation, the focus group was integrated into an action research framework with students. This method was anticipated to foster openness and facilitate the sharing of views. The teacher's role was to guide the discussion, pose questions, and encourage participation. Initially, pupils were prompted to respond to a set of questions ("*What did you like most when we were using augmented reality apps on iPads?*" "*Could the application help you visualize shapes that you only had seen on paper before?*" "*Did you learn something new?*" "*What did not you like?*" "*Would you like to use this application in other lessons as well?*" "*What was the work like in groups*") designed to elicit their experiences with augmented reality applications on iPads.

A digital dictaphone recorded the discussions. The responses offered insights into the pupils' engagement with the augmented reality application. These recordings were subsequently transcribed, and open coding was applied to the transcript to establish thematic categories (Table 1).

The pupils worked both individually and collaboratively within their groups, contributing to a shared objective while also pursuing their personal learning goals (Figure 2). The group dynamic was characterized by mutual respect and shared experiences. Unbeknownst to the students, their interaction with the images contributed to their learning process (Figure 3). Both direct and indirect observations were documented in a written Table (see Table 1).

Indirect observation sought to identify the presence and frequency of specific phenomena within various contexts.

Analysis of the pupils' discourse during the focus group sessions involved an inclusive approach to discern the optimal use of augmented reality within educational practices. The open coding process facilitated the exploration, comparison, categorization, coding, and conceptualizing of the data collected.

The principal concepts articulated within individual statements were extracted and systematically categorized within the statement protocol (Table 2).

## 5.5 Quantitative method

### 5.5.1 Research questions

What impact does the Quiver application have on pupils' during online education?

TABLE 1 Statement snippets of pupils from the focus group.

| Question | Statement snippets of pupils (with Quiver application) | Statement snippets of pupils (without Quiver application) |
|---|---|---|
| What did you like? | I liked when the body showed above the desk. /VD/ | I liked the pictures. /VD/ |
| | I liked when things on paper became alive. /PH/ | I did not like anything. /VD/ |
| | I liked being able to work with my classmates and show them my body. /MFV/ | I liked working in the group. /MFV/ |
| | I liked when we were working with a tablet and not just sitting at a desk. / MFV/ | |
| | I liked that a triangle was burning above a desk. /VD/ | |
| | I liked that I could compare the cube with a classmate while he was having the same one, but a different color. /MFV/ | |
| | I liked everything. /RU/ | |
| What did you learn? | I learned to work with Quiver more. /VD/ | I learned how to make a square and how many sides other solids have. /VD/ |
| | I learned how to make a square and how many sides other solids have. /VD/ | I did not learn anything. /VD/ |
| | I learned what the formation looks like before I put it together. And how many walls other bodies have compared the ones I know. /VD/ | |
| | I did not learn anything, I just played with the iPad and saw what would happen. /VD/ | |
| | I did not learn anything, I just colored shapes, but it was good. /VD/ | |
| Were you surprised by anything? | I was surprised how things could be the way I colored them. /PH/ | I wasn't surprised by anything. /VD/ |
| | I was surprised how a formation could fly over a paper. /VD/ | |
| | I was surprised that the lesson went by so quickly. Mathematics always runs slowly. /MFV/ | |
| | I was surprised that all my classmates were cooperating with me. /PH/ | |
| | I was surprised that the teacher let us work alone. /VD/ | |
| | After a while I stopped enjoying it. The same thing always happened. /PH/ | |
| | It was better than last time when sheets could not be loaded. /MFV/ | |
| Would you like anything for next time? | I would like to have a tablet during each lesson. /MFV/ | I would like to have a tablet. /MFV/ |
| | I would like to have a tablet for 1 h a day at least. /MFV/ | I would like to see the pictures in another way. / MFV/ |
| | I wish we had more iPads than we have. /MFV/ | |
| | I wish everything in mathematics could be explained via a tablet. /MFV/ | |

How do parents perceive the Quiver application within the context of their children's learning?

Can Augmented Reality (AR) enhance motivation, knowledge, creativity, and collaborative skills among children?

Our investigation sought to discern parents' perceptions and attitudes towards the utilization of AR in online education. The pupils were familiar with the Quiver application from school and extended its use to home settings via smartphones or tablets. The study aimed to substantiate or disprove the hypothesis: Parents believe that the Quiver application fosters student motivation and contributes to increased knowledge and creativity.

## 5.6 Statistical analysis of research focus areas

The statistical analyses targeted the issues related to the use of Quiver, employing descriptive statistics and analysis of interdependencies among identified variables. Methodological rigor was ensured by adhering to standards of statistical significance as delineated in contemporary research (Gauthier and Hawley, 2015; Kitchenham et al., 2017; Barot and Krpec, 2019). Key variables and statistical outcomes are delineated in the following table, with abbreviations clarified for ease of reference:

Table 3 presents the descriptive statistical parameters corresponding to the Likert scale responses provided by the participants. This scale was composed of statements to which the respondent can answer on a scale representing the degree of agreement. There were offers on a scale of I completely agree, I agree, I have no strong opinion, I disagree, I do not agree at all. The number of possible answers, their specific naming, or the inclusion or exclusion of the median value may vary according to the specific application. The Likert scale makes it possible to determine not only the content of the attitude, but also its approximate strength.

Additionally, Figure 4 offers a graphical representation of these outcomes in the form of a boxplot for visual interpretation of the data distribution (Table 4).

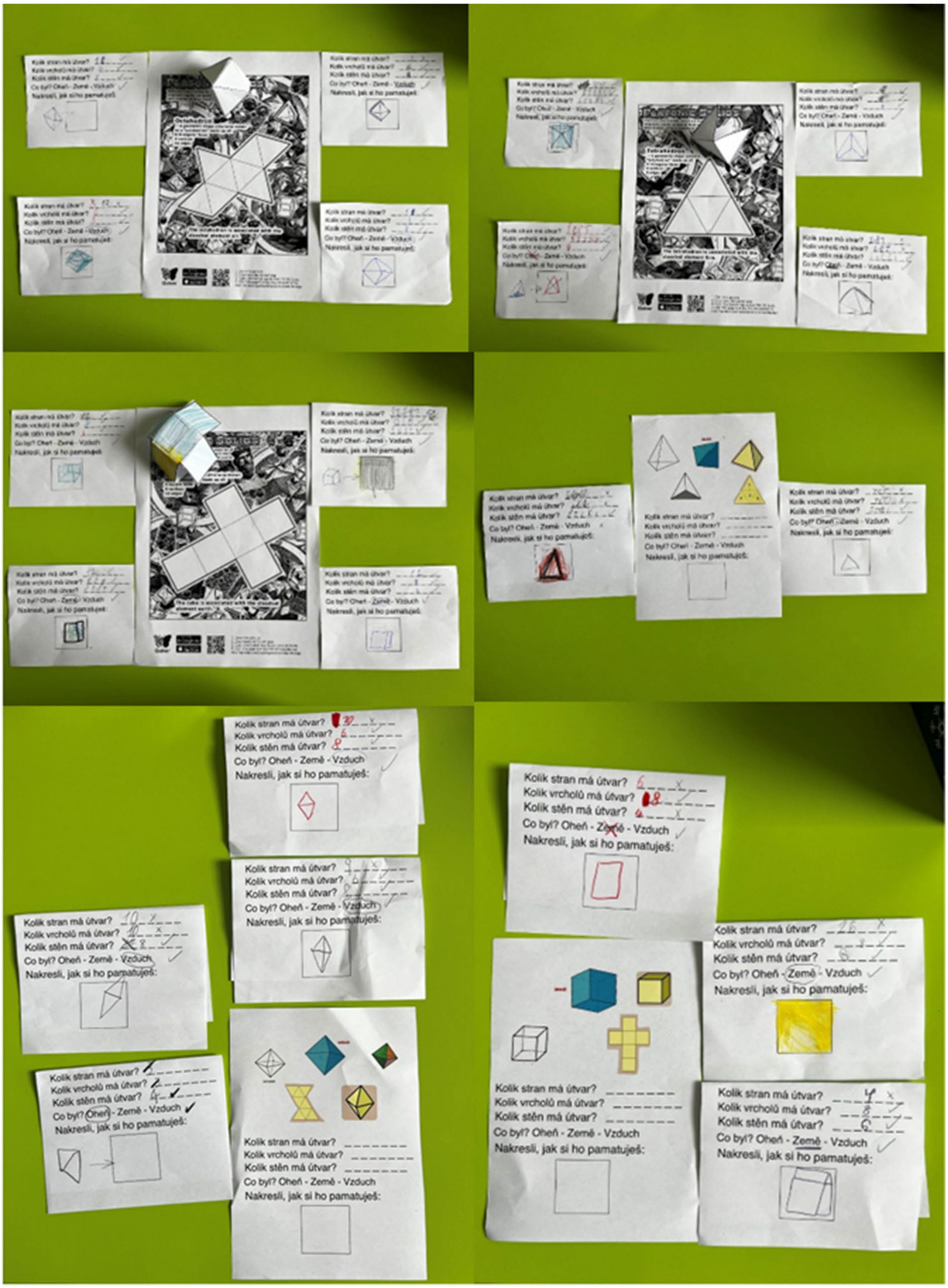


FIGURE 3
Examples of pupils' work in the classroom.

TABLE 2 List of identified categories, concepts, and codes in Table 1.

| Interpretative category | Concepts | Codes |
|---|---|---|
| The teacher's role | Teacher as an advisor, a listener, an observer. | RU |
| Teaching methods and forms | Group work.<br>Individual work.<br>Working with a tablet.<br>Working without a tablet. | MFV |
| Child's performance | The child is improving his/her potential and abilities.<br>The child decides independently.<br>The child gets information in different ways.<br>The child can find out how to perform a certain activity. | VD |
| Added value | The child carries out the activity independently.<br>The teacher realizes teaching by his / her individuality. | PH |

TABLE 3 Glossary of abbreviations for analysed research variables.

| Item Nr. | Clarification of proposed items' content |
|---|---|
| Item 1 | I knew (as a parent) the Quiver application (with augmented reality) before entering work from school. |
| Item 2 | When my child worked with Quiver (augmented reality) during distance learning, the work motivated him. |
| Item 3 | When my child worked with Quiver (with augmented reality), he learned more. |
| Item 4 | When working with Quiver (augmented reality), my child played rather than taught. |
| Item 5 | The child was able to work independently with the Quiver application (with augmented reality). |
| Item 6 | The child needed help with Quiver (augmented reality) during startup and installation. |
| Item 7 | My child was creative when working with Quiver (augmented reality). |
| Item 8 | My child wanted to work with the Quiver application (with augmented reality) even outside of school assignments. |
| Item 9 | The Quiver application (with augmented reality) also attracted my parents (or other family members). |
| Item 10 | I think Quiver or similar augmented reality applications should be included in teaching (used more often). |

The analysis of the interactions among the variables under study reveals correlational relationships, which are depicted in Figure 5.

In this study, we further investigate the observed interactions among specified variables. For sets comprising both dependent and independent variables of a cardinal nature, multiple regression analysis is deemed an appropriate method to examine the interrelations among the variables in question. A significance level of 0.05 has been adopted. The application of mathematical induction methods, utilizing *p*-values, facilitates the verification of the correlations among specific outcomes.

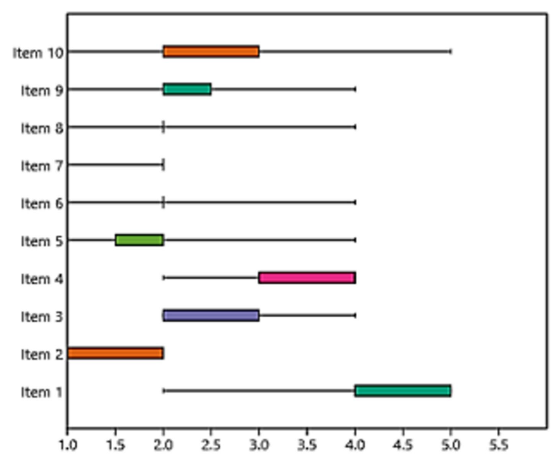


FIGURE 4
Descriptive statistical approach to achieved analysed items.

### 5.6.1 Situation 1—considered variables: Item 1 + Item 9 + Item 10

This scenario examines whether prior familiarity with the Quiver platform influenced parental attitudes towards its subsequent integration into educational practices. The variables analyzed were:

Item 1: Familiarity with the Quiver application before it was introduced in the school setting.

Item 9: The extent to which parents found the Quiver application engaging.

Item 10: Parents' opinions on whether the Quiver application should be more frequently integrated into the curriculum.

The statistical analysis involved multiple regression to understand the relationship between these variables (Table 5).

The constant value of 4.4033 indicates a high baseline level of support for integrating the Quiver application into educational practices, regardless of prior familiarity. The coefficients for Items 9 and 10 were relatively small and not statistically significant, as indicated by the high *p*-values (0.62774 and 0.46147, respectively). This suggests that neither the engagement level (Item 9) nor the belief that Quiver should be more integrated into the curriculum (Item 10) were significantly influenced by prior familiarity with the platform.

Analysis: The $R^2$ value is very low (7.82E-05 for Item 9 and 0.014258 for Item 10), indicating that the model explains very little of the variance in parental attitudes based on the variables considered. This low explanatory power suggests that other factors not included in this model may play a more significant role in shaping parental attitudes towards the Quiver application. The *t*-values are low (0.49179 and −0.74954), further supporting the lack of significant relationships. The *p*-values are much higher than the common significance threshold of 0.05, reinforcing the conclusion that there are no statistically significant interactions among the observed variables.

Interim Conclusion: The analysis did not reveal any statistically significant interactions among the variables considered (prior familiarity, engagement, and opinion on integration). This suggests that parents' support for the Quiver application in educational practices is not strongly influenced by their previous familiarity with

TABLE 4 Obtained descriptive statistics for proposed research items according to analysis of quiver impact.

| | Item 1 | Item 2 | Item 3 | Item 4 | Item 5 | Item 6 | Item 7 | Item 8 | Item 9 | Item 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| *N* | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 | 25 |
| Min | 2 | 1 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| Max | 5 | 2 | 4 | 4 | 4 | 4 | 2 | 4 | 4 | 5 |
| Sum | 106 | 41 | 63 | 85 | 46 | 54 | 45 | 53 | 59 | 59 |
| Mean | 4.24 | 1.64 | 2.52 | 3.4 | 1.84 | 2.16 | 1.8 | 2.12 | 2.36 | 2.36 |
| Std. error | 0.166133 | 0.09798 | 0.16452 | 0.163299 | 0.1249 | 0.14922 | 0.08165 | 0.156205 | 0.181475 | 0.181475 |
| Variance | 0.69 | 0.24 | 0.676667 | 0.666667 | 0.39 | 0.556667 | 0.166667 | 0.61 | 0.823333 | 0.823333 |
| Stand. dev. | 0.830662 | 0.489898 | 0.822598 | 0.816497 | 0.6245 | 0.746101 | 0.408248 | 0.781025 | 0.907377 | 0.907377 |
| Median | 4 | 2 | 2 | 4 | 2 | 2 | 2 | 2 | 2 | 2 |
| 25 prcntil | 4 | 1 | 2 | 3 | 1.5 | 2 | 2 | 2 | 2 | 2 |
| 75 prcntil | 5 | 2 | 3 | 4 | 2 | 2 | 2 | 2 | 2.5 | 3 |
| Skewness | −1.44357 | −0.62125 | 1.15135 | −0.89859 | 1.2264 | 1.688549 | −1.59749 | 1.491178 | 0.999843 | 0.999843 |
| Kurtosis | 2.625665 | −1.76219 | −0.44684 | −0.85227 | 5.300497 | 3.15229 | 0.592885 | 2.655264 | 0.016929 | 1.911938 |
| Geom. mean | 4.137534 | 1.558329 | 2.411942 | 3.287504 | 1.741101 | 2.056228 | 1.741101 | 2 | 2.209008 | 2.198724 |
| Coeff. var | 19.59109 | 29.87183 | 32.64276 | 24.01461 | 33.94021 | 34.54171 | 22.68046 | 36.8408 | 38.44819 | 38.44819 |

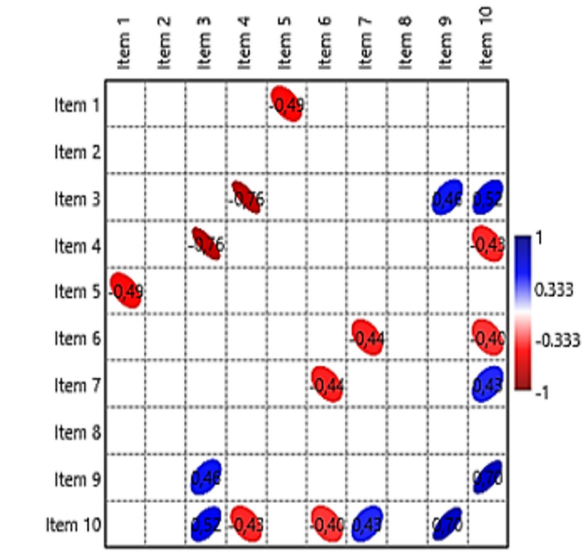


FIGURE 5
Visual form of presentation of interaction between items as correlations of given scale of intensity.

TABLE 5 The statistical analysis in situation 1.

| | Coeff. | Std. error | *t* | *p* | $R^2$ |
|---|---|---|---|---|---|
| Constant | 4.4033 | 0.52273 | 8.4237 | 2.48E-08 | |
| Item 9 | 0.13206 | 0.26853 | 0.49179 | 0.62774 | 7.82E-05 |
| Item 10 | −0.20127 | 0.26853 | −0.74954 | 0.46147 | 0.014258 |

the platform. Other factors, potentially including direct observation of their children's engagement and learning outcomes, may be more critical in shaping their attitudes.

TABLE 6 The statistical analysis in situation 2.

| | Coeff. | Std. error | *t* | *p* | $R^2$ |
|---|---|---|---|---|---|
| Constant | 2.0804 | 0.40929 | 5.083 | 4.31E-05 | |
| Item 3 | −0.07027 | 0.12381 | −0.56753 | 0.5761 | 1.86E-02 |
| Item 8 | −0.12424 | 0.1304 | −0.95275 | 0.35107 | 0.043716 |

Future research should explore additional variables that could influence parental attitudes, such as direct feedback from their children, observed improvements in academic performance, or the perceived ease of use and technical reliability of the application. This broader approach may provide a more comprehensive understanding of the factors driving parental support for AR technologies in education.

### 5.6.2 Situation 2—observed aspects: Item 2 + Item 3 + Item 8

This scenario examines whether the Quiver application proved to be a motivator for children, potentially increasing their learning engagement and willingness to extend educational activities beyond formal schoolwork. The variables analyzed were:

Item 2: The degree to which the Quiver application motivated children during distance learning.

Item 3: The extent to which children learned more while using the Quiver application.

Item 8: The willingness of children to use the Quiver application outside of assigned schoolwork.

The statistical analysis involved multiple regression to understand the relationship between these variables (Table 6).

The constant value of 2.0804 suggests a moderate baseline level of motivation among children to use the Quiver application. The coefficients for Items 3 and 8 were negative and not statistically significant, as indicated by the high *p*-values (0.5761 and 0.35107, respectively). This suggests that neither the amount learned (Item 3) nor the willingness to use Quiver outside of schoolwork (Item 8) were significantly related to the motivation level measured in Item 2.

Analysis: The $R^2$ values are very low (1.86E-02 for Item 3 and 0.043716 for Item 8), indicating that the model explains very little of the variance in children's motivation based on the variables considered. This low explanatory power suggests that other factors not included in this model may play a more significant role in influencing children's motivation to use the Quiver application. The *t*-values are low (−0.56753 and −0.95275), further supporting the lack of significant relationships. The *p*-values are much higher than the common significance threshold of 0.05, reinforcing the conclusion that there are no statistically significant interactions among the observed variables. The negative coefficients for Items 3 and 8 indicate that there is no positive relationship between these variables and the motivation level. However, given the lack of statistical significance, these relationships are not meaningful.

Interim Conclusion: The data did not reveal any statistically significant interactions among the variables considered (motivation during distance learning, increased learning, and willingness to use the application outside of schoolwork). This suggests that children's motivation to use the Quiver application is not strongly influenced by the amount they learn or their willingness to use it outside formal school assignments.

Future research should explore additional variables that could influence children's motivation, such as the novelty effect of the technology, peer interactions, and the specific features of the Quiver application that may drive engagement. A broader approach, including qualitative feedback from children about their experiences and preferences, may provide a more comprehensive understanding of the factors driving their motivation to use AR technologies in education.

### 5.6.3 Situation 3—observed aspects: Item 9 + Item 4

This scenario examines whether the Quiver application's ability to make a favorable impression influenced the balance between children's engagement in play versus learning activities. The variables analyzed were:

Item 9: The extent to which parents found the Quiver application engaging.

Item 4: The degree to which children played rather than engaged in educational activities while using the Quiver application.

The statistical analysis involved multiple regression to understand the relationship between these variables (Table 7).

TABLE 7 The statistical analysis in situation 3.

| | Coeff. | Std. error | *t* | *p* | $R^2$ |
|---|---|---|---|---|---|
| Constant | 3.3375 | 0.78182 | 4.2689 | 2.88E-04 | |
| Item 4 | −0.2875 | 0.22383 | −1.2844 | 0.21178 | 6.69E-02 |

The constant value of 3.3375 suggests a relatively high baseline perception of the Quiver application making a favorable impression. The coefficient for Item 4 was negative, indicating a potential inverse relationship between the application's favorable impression and children's engagement in play rather than learning. However, this relationship was not statistically significant, as indicated by the high *p*-value (0.21178).

Analysis: The $R^2$ value (6.69E-02) indicates that the model explains only a small portion of the variance in the balance between play and learning activities based on the variables considered. This low explanatory power suggests that other factors not included in this model may have a more substantial impact on how children use the Quiver application. The *t*-value (−1.2844) and the *p*-value (0.21178) further support the lack of significant relationship between the observed variables. The *p*-value is higher than the common significance threshold of 0.05, indicating that the observed relationship is not statistically significant. The negative coefficient for Item 4 suggests that a less favorable impression of the Quiver application might lead to more play-oriented activities rather than learning-focused activities. However, given the lack of statistical significance, this relationship is not robust and should be interpreted with caution.

Interim Conclusion: The data did not reveal any statistically significant interactions between the application's favorable impression (Item 9) and the extent of play versus learning activities (Item 4). This suggests that children's tendency to engage in play rather than learning activities while using the Quiver application is not strongly influenced by the application's initial impression on parents.

Future research should investigate additional factors that may influence the balance between play and learning activities. These could include the specific design features of the application, the context in which it is used, the role of teacher guidance, and the individual learning styles and preferences of children. A mixed-methods approach, combining quantitative data with qualitative insights from children, parents, and teachers, may provide a more comprehensive understanding of how to maximize the educational benefits of AR applications like Quiver.

### 5.6.4 Situation 4—observed aspects: Item 5 + Item 6

This scenario examines the relationship between children's ability to work independently with the Quiver application (Item 5) and the need for assistance during its use (Item 6). The variables analyzed were:

Item 5: The child's ability to work independently with the Quiver application.

Item 6: The need for help with the Quiver application during startup and installation.

The statistical analysis involved multiple regression to understand the relationship between these variables (Table 8).

The constant value of 2.3832 suggests a moderately high baseline level of independent work capability among children. The negative coefficient for Item 6 indicates a potential inverse relationship between the need for assistance and the child's ability to work independently. However, this relationship was not statistically significant, as indicated by the high *p*-value (0.14446).

Analysis: The $R^2$ value (9.03E-02) indicates that the model explains a small portion of the variance in the children's ability to work independently based on the need for assistance. This low explanatory power suggests that other factors not included in this model may significantly influence children's independent use of the Quiver application. The *t*-value (−1.5108) and the *p*-value (0.14446) further support the lack of a significant relationship between the observed variables. The *p*-value is higher than the common significance threshold of 0.05, indicating that the observed relationship is not statistically significant. The negative coefficient for Item 6 suggests that as the need for help decreases, the child's ability to work independently increases. However, given the lack of statistical

TABLE 8 The statistical analysis in situation 4.

| | Coeff. | Std. error | *t* | *p* | $R^2$ |
|---|---|---|---|---|---|
| Constant | 2.3832 | 0.3796 | 6.2783 | 2.09E-06 | |
| Item 6 | −0.2515 | 0.16647 | −1.5108 | 0.14446 | 9.03E-02 |

significance, this relationship is not robust and should be interpreted with caution.

Interim Conclusion: The data did not reveal any statistically significant interactions between the child's ability to work independently with the Quiver application (Item 5) and the need for assistance during its use (Item 6). This suggests that the level of independence in using the Quiver application is not strongly influenced by the initial need for assistance.

Future research should explore additional factors that may influence children's ability to work independently with educational technology. These could include the child's prior experience with similar technologies, the complexity of the application, the availability of instructional support, and individual differences in learning styles and technological proficiency. A mixed-methods approach, incorporating both quantitative data and qualitative feedback from children and educators, may provide a more comprehensive understanding of how to foster independent use of AR applications like Quiver.

### 5.6.5 Situation 5—observed aspects: Item 7 + Item 3 + Item 9

This scenario examines whether a child's creativity, as observed through their use of the Quiver application, correlates with higher learning uptake and subsequently increases parental interest and involvement. The variables analyzed were:

Item 7: The child's creativity when working with the Quiver application.

Item 3: The extent to which children learned more while using the Quiver application.

Item 9: The extent to which parents found the Quiver application engaging.

The statistical analysis involved multiple regression to understand the relationship between these variables (Table 9).

TABLE 9 The statistical analysis in situation 5.

| | Coeff. | Std. error | *t* | *p* | $R^2$ |
|---|---|---|---|---|---|
| Constant | 1.4151 | 0.28697 | 4.9312 | 6.22E-05 | |
| Item 3 | 0.033058 | 0.11318 | 0.29209 | 0.77296 | 3.94E-02 |
| Item 9 | 0.12778 | 0.1026 | 1.2454 | 0.22609 | 0.09919 |

The constant value of 1.4151 suggests a baseline level of positive correlation between creativity and learning uptake. The coefficients for Items 3 and 9 were positive, indicating a potential direct relationship with the dependent variable. However, these relationships were not statistically significant, as indicated by the high *p*-values (0.77296 for Item 3 and 0.22609 for Item 9).

Analysis: The $R^2$ values are very low (3.94E-02 for Item 3 and 0.09919 for Item 9), indicating that the model explains only a small portion of the variance in learning uptake and parental interest based on the variables considered. This low explanatory power suggests that other factors not included in this model may have a more substantial impact. The *t*-values (0.29209 for Item 3 and 1.2454 for Item 9) and the *p*-values (0.77296 and 0.22609) further support the lack of significant relationships between the observed variables. The *p*-values are higher than the common significance threshold of 0.05, indicating that the observed relationships are not statistically significant. The positive coefficients for Items 3 and 9 suggest a potential positive relationship between children's creativity, learning uptake, and parental engagement. However, given the lack of statistical significance, these relationships are not robust and should be interpreted with caution.

Interim Conclusion: The data did not reveal any statistically significant interactions between a child's creativity (Item 7), learning uptake (Item 3), and parental interest and involvement (Item 9). This suggests that while there may be a perceived relationship between these factors, it is not strongly supported by the data in this analysis.

Future research should explore additional factors that may influence the observed relationships. These could include qualitative insights from parents and children, the specific types of creative activities engaged in, the role of teacher facilitation, and the broader educational context. A mixed-methods approach, combining quantitative data with qualitative feedback, may provide a more comprehensive understanding of how creativity in using AR applications like Quiver impacts learning and parental involvement.

## 6 Conclusion and discussion

The qualitative analysis of observations and focus group discussions indicates that the Quiver application significantly enhances students' engagement, collaboration, and conceptual understanding in learning geometry. The positive feedback from students and their willingness to use similar applications in other lessons underscore the potential of AR to transform educational experiences. This analysis clarifies the specific advantages and potential obstacles associated with using AR in primary education.

In the current educational landscape, digital technologies have become a sought-after resource. Their utility extends beyond mere motivation; they engage multiple senses simultaneously, thereby facilitating a more indelible assimilation of the curriculum. The objective of this research was to observe pupils' reactions while integrating IT technology (AR Quiver app) into the class on the topic of Platonic solids. A main goal was to assess the influence and advantages of AR in the enhancement of children's digital literacy.

Within the Focus Group, we observed an increase in students' motivation to work on the assigned task. The introduction of AR proved to be considerably effective in advancing the digital literacy of the participating pupils. While interacting with tablets and AR, high levels of engagement, motivation, and collaborative communication were evident. Pupils demonstrated the ability to discern between real and virtual environments.

The impact of the Quiver application was consistent across both online and traditional classroom settings was found to be consistent. The determining factor for successful application use was the children's ability to work with mobile apps and their capacity to utilize these applications at home independently of teacher presence. It was observed that if children were adept at using the application in school, transitioning to home use presented no significant challenges.

Moreover, the advent of sophisticated communication platforms such as Google Meet has facilitated seamless interaction among students outside the classroom.

In conclusion, the Quiver application's ability to enhance digital literacy, engagement, and collaborative learning among primary school students positions it as a valuable tool in modern education. The study highlights the importance of integrating such technologies thoughtfully to maximize their educational benefits and address any potential challenges effectively.

Additionally, the statistics revealed (Table 4) that the obtained calculations show that students with previous experience with the Quiver application are able to use this application independently at home without the help of their parents. Parents perceive this application as functional and appropriate.

## Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

## Ethics statement

The studies involving human participants were reviewed and approved by the Ethics Committee for Research of the Faculty of Education, University of Ostrava. Written informed consent from the participants was not required to participate in this study in accordance with the national legislation and the institutional requirements.

## Author contributions

NN: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. LK: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. ZL: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. NB: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization. AS: Writing – original draft, Writing – review & editing, Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization.

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## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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