How ninth graders perceive tasks with curricular overlap: The case of mathematics and chemistry

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Abstract: This paper presents a qualitative empirical study focusing on the way in which lower-secondary school students without STEM experience perceive tasks with cross-curricular overlap, namely tasks that include both mathematics and chemistry content (ratio and stoichiometry). We prepared a worksheet with six tasks to solve and seven groups of questions to answer and assigned it to 40 ninth-graders from three different schools in a country where STEM education does not have a tradition. The study revealed that the students mostly perceive the subjects of mathematics and chemistry as distinct and tend to perceive problems with chemistry terms in the assignment as purely chemical even if a mathematical content is included in them and mathematical procedures could be used to solve them.

Keywords: cross-curricular problem solving, STEM education, ratio, stoichiometry

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1 Introduction

Mathematics and science education play a key role in preparing students for life in a rapidly changing and technology-dependent society (English, 2017). According to the results of the PISA assessment study (European Commission, 2022), almost a quarter of 15-year-olds in the EU-27 were below even the basic level in mathematics and science. Analysis of these and other large-scale international comparative assessment studies has prompted research into STEM education (English, 2017).

STEM education, as defined by Moore et al. (2014), is an educational approach that aims to integrate some or all the four disciplines of **S**cience, **T**echnology, **E**ngineering, and **M**athematics into a single lesson. This integration is based on the premise that these subjects can be connected to real-world problems. It is not necessary for all four disciplines to be included to the same degree in any given activity, nor is it necessary for a single activity to include all four disciplines. Furthermore, there is no consensus on whether the knowledge support is for individual disciplines or an integrated approach. According to Stohlmann (2019), it is even sufficient to include only two disciplines to create STEM learning. Doğan et al. (2019) argue that mathematics must be a critical component of STEM learning; however, it seems that the STEM approach tends to support scientific development more than mathematical outcomes (Honey et al., 2014). Therefore, educators strive to balance real-world challenges with the integration of mathematical skills. STEM education can help students see the practical relevance of mathematics, which in turn provides analytical tools for other STEM areas (Fitzallen, 2015).

The objective of this paper is to present the findings of an empirical qualitative study that examines students' perceptions of STEM tasks. We focus on tasks integrating mathematics and chemistry educational content and on ninth graders (aged 14–15) from a country where STEM education does not have a tradition. The focus of this study is on how these students perceive such tasks and whether they are aware of the possibility to apply mathematical procedures when solving chemistry problems. Within this context, the research question is as follows:

RQ: Are the students able to identify mathematical topics included in the tasks and are they aware of the possibility to apply mathematical procedures when solving them?

2 The context of the study

In the Czech Republic, STEM education does not have a tradition, and, moreover, in secondary schools the discipline of science is divided into three individual school subjects: biology, chemistry, and physics. However, the climate is gradually changing, and steps are being taken to improve the situation. For instance, recently at our faculty, we have been working on a grant project named *Key areas of the curriculum for the integration of education content in the field of STEM*, where we study various possibilities for integration that are enabled and allowed by our curricular documents. As part of the project, we reviewed 24 Czech textbooks for lower-secondary students (aged 11–15) from six school subjects: mathematics, chemistry, biology, geography, physics, and technical education, in relation to the STEM concept (Rokos et al., 2023). The review identified various STEM-related tasks that could support its integration into education. These tasks were classified by assignment type, contextual plausibility, and cross-curricular learning potential. This paper focuses on the latter.

The cross-curricular learning potential is evaluated based on the level of integration between subject contents and the extent to which learners are required to shift between the subjects during problem solving. In tasks with no potential, concepts from different subjects are not connected, and the learner either has no need to switch between subjects or switches only once. For instance, the task in Table 1 has no potential, since the solver can solve it using just algorithmic procedures learnt in chemistry lessons, without switching to the mathematical topic of ratios. In tasks with weak potential, there is a need for one switch back and forth. Adding a question *How do the coefficients relate to the N to H ratio and why?* to the task in Table 1 would ensure this switch. Tasks with strong cross-curricular potential require repetitive switching between concepts or subjects. In the task shown in Table 1, this potential could be achieved by deepening the link between mathematics and chemistry (e.g. through molar mass or targeted questions), or by relating the task to a practical issue such as sustainable hydrogen storage (David et al., 2014) which involves knowledge from mathematics, chemistry, biology, physics, technology, and engineering.

Table 1. An illustrative task

Add the stoichiometric coefficients to the chemical equation: $NH_3 \longrightarrow H_2 + N_2$

What remains to be investigated is the student perspective, that is, how Czech students perceive tasks with potential for cross-curricular learning and whether they can see various school subjects as something that can be interconnected by overlapping contents and concepts. As we are just starting to map the terrain of cross-curricular handling of tasks in classrooms without STEM experience, we focus on tasks that include only two school subjects (mathematics and chemistry) and exclude tasks with strong potential to keep things simple and better interpretable. Some tasks still link mathematical and chemistry concepts.

2.1 Cross-curricular overlap between mathematics and chemistry

To explore the overlap between mathematics and chemistry, we focus on the topic of ratios and their applications in molar mass and stoichiometry (the determination of the proportions in which elements or compounds react with one another). Gabel et al. (1984) found that students often rely on memorised algorithms when solving such problems, lacking understanding of the underlying chemistry. Similarly, Ramful and Narod (2014) showed that prospective chemistry teachers struggled to transfer ratio knowledge from mathematics to chemistry. Anggraeni et al. (2022) demonstrated that the EIGER strategy (Engage, Investigation, Guided-connection, Evaluation, and Reflection) significantly improves students' conceptual and algorithmic understanding in stoichiometry.

3 Materials and methods

3.1 Participants

Our study was conducted with three ninth-grade classes from three lower-secondary schools in the South Bohemia region and Vysočina Region of the Czech Republic. A total of 40 students aged between 14 and 15 years were involved. Their chemistry lessons already covered the topics of molar mass, and the law of the conservation of mass; their mathematics lessons already covered the topic of ratios. These students had no experience with STEM education or cross-curricular tasks. Their teacher of mathematics and teacher of chemistry were different people.

3.2 Data collection instrument

As a data collection instrument, we created a worksheet with a set of tasks with gradually in-creasing interconnectedness of mathematical and chemistry concepts (Table 2), accompanied by a set of questions to reflect on the process of solving the tasks (Table 3). The first author created the set, and the second author validated it; the final form was established after mutual discussions.

Table 2. Tasks in the worksheet; abbreviations: M=Mathematics, C=Chemistry

<table>
<tr><th>Task code</th><th>Tasks assignment</th><th>Included knowledge</th></tr>
<tr><td rowspan="2">T1</td><td rowspan="2">Add the stoichiometric coefficients to the chemical equations:
$NaF \longrightarrow Na + F_2$
$NH_3 \longrightarrow H_2 + N_2$
$Mn + O_2 \longrightarrow Mn_2O_7$</td><td>M:
divisibility, ratio</td></tr>
<tr><td>C:
the law of the conser-vation of mass</td></tr>
<tr><td rowspan="2">T2</td><td rowspan="2">Calculate the molar mass of the compound with the formula Na_2SO_4.
<table><tr><th>element</th><th>g/mol</th></tr><tr><td>O</td><td>16</td></tr><tr><td>Na</td><td>23</td></tr><tr><td>S</td><td>32</td></tr></table></td><td>M:
elementary arithmetic operations</td></tr>
<tr><td>C:
molar mass</td></tr>
<tr><td rowspan="2">T3</td><td rowspan="2">On the label of the syrup is recommended dilution with water in a ratio of 1:10. The syrup is sold in bottles of 700 ml. How many ml of drink can be made from one bottle of syrup?</td><td>M:
ratio</td></tr>
<tr><td>C:
solutions</td></tr>
</table>

<table>
<tr>
<td rowspan="2">T4</td>
<td rowspan="2">A chemical equation is given, but one element is missing. Use the following clues to find out which element it is. The ratio of the molar mass of carbon (C) to the molar mass of the element you are looking for is 3:7. Find the element in the periodic table of elements.
<table><tr><th>element</th><th>g/mol</th></tr><tr><td>C</td><td>12</td></tr><tr><td>O</td><td>16</td></tr><tr><td>[ ]</td><td></td></tr></table>
$2\,C + [\quad]O_2 \longrightarrow 2\,CO + [\quad]$</td>
<td>M:
ratio</td>
</tr>
<tr>
<td>C:
molar mass, the law of the conservation of mass</td>
</tr>
<tr>
<td rowspan="2">T5</td>
<td rowspan="2">Add the stoichiometric coefficients to the chemical equation. Find the ratio of the masses of the elements in the compound CaO. How many grams of calcium and how many grams of oxygen are produced from 490 grams of CaO?
<table><tr><th>element</th><th>g/mol</th></tr><tr><td>O</td><td>16</td></tr><tr><td>Ca</td><td>40</td></tr></table>
$CaO \longrightarrow \quad Ca + \quad O_2$</td>
<td>M:
divisibility, ratio</td>
</tr>
<tr>
<td>C:
molar mass, the law of the conservation of mass</td>
</tr>
<tr>
<td rowspan="2">T6</td>
<td rowspan="2">Using the chemical equation, find how many g of Al and SiO_2 were used to prepare 408 g of Al_2O_3. First, add the stoichiometric coefficients to the chemical equation.
<table><tr><th>element</th><th>g/mol</th></tr><tr><td>O</td><td>16</td></tr><tr><td>Al</td><td>27</td></tr><tr><td>Si</td><td>28</td></tr></table>
$Al + \quad SiO_2 \longrightarrow \quad Al_2O_3 + \quad Si$</td>
<td>M:
ratio</td>
</tr>
<tr>
<td>C:
molar mass, the law of the conservation of mass</td>
</tr>
</table>

Table 3. Questions in the worksheet

Code	Question(s)
Q1	The following topics were used to solve today's problems a) math: b) chemistry:
Q2	I would label tasks # ____ as math tasks because _____.
Q3	I would label tasks # ____ as chemistry tasks because _____.
Q4	I'm more comfortable with math/chemistry tasks because _____.
Q5	I prefer to solve math/chemistry tasks because _____.
Q6	What I found interesting about today's tasks was _____.
Q7	Were mathematical and chemical procedures combined in some problems? In which ones? Does it have any advantages?

The tasks in the set are related to the mathematical topic of ratio, the chemistry topic of the law of the conservation of mass and/or the chemistry topic of molar mass.

Tasks T1 to T3 are introductory and can be considered tasks with no potential for cross-curricular learning. The reason for their inclusion in the set is that they serve as a kind of hint to the more complex tasks which follow. Task T4 has a low potential. Tasks T5 and T6 can be considered chemistry tasks and as such can be solved using just algorithms learnt during chemistry lessons; however, applying mathematical procedures, especially ratios, can lead to more efficient and simpler solutions.

3.3 Data collection and data analysis

Data collection took part during standard chemistry lessons of the participants. We passed the data collection instrument to their chemistry teachers and let the teachers themselves administer the data collection part of the study. The students were asked to solve all the tasks in the worksheet and then respond to the accompanying questions. The process of data collection was anonymous; each student was randomly assigned a code name between S01 and S40.

During data analysis, we first analysed the responses to the questions, and then contrasted the opinions presented in answers with the methods the students used for solving the tasks. We analysed our data qualitatively, using open coding and constant comparison (Miles et al., 2014). Triangulation (Flick, 2018) was applied regarding data (different types of data: task solutions vs answers to reflective questions; data collected from different groups of participants in different settings: three classes in three different schools led by three different teachers) as well as researchers. Both authors participated in data analysis, repeatedly discussed and compared their individual findings and experiences.

4 Results

After analysing all students' responses, we narrowed our focus to Q1, Q2, Q3, and Q7 questions, as they had the most relevant information, and their data was dense.

4.1 Included topics mentioned in answers

In responses to Q1, the students mentioned mathematical topics of arithmetic operations, ratios, cross-multiplication, and equations; the topic of ratios was present in most responses. As chemistry topics, the students mentioned the nomenclature of compounds, molar mass, solutions (in relation to task T3), and the enumeration of chemical equations. In responses to Q2, students most often classified T3 as a mathematical task and reasoned that they used mathematical procedures when solving this task (for data excerpts, see Table 4). As chemistry tasks, students most frequently labelled all the other tasks, and reasoned that chemical terms were present in the assignment of these tasks (for data excerpts, see Table 5). Some of the students were not able to distinguish mathematics and chemistry tasks (S10 in Table 5). Student S40 labelled tasks T1–T4 as chemistry tasks because their solutions involve only basic mathematics.

Table 4. Students' reactions to Q2 – tasks labelled as mathematics tasks

Student code	Reactions to Q2
S21	I would label problems 2, 3, 5 as math problems because I can do them without knowing chemistry.
S08	...#3, because I only use math for that.
S33	...#2, 4, because I used addition and division for both tasks.

Table 5. Students' reactions to Q3 – tasks labelled as chemistry tasks

Student code	Reactions to Q3
S22	I would label problems 1, 2, 4 as chemical because we had to add the stoichiometric coefficients to the chemical equation, use formulas and look for elements.
S21	...#1, 4, 6, because I can't do them without knowing chemistry.
S08	...#1, 2, 4, 5, 6, because there are elements and molar masses.
S10	...# I don't know, because I have no idea if the problems were chemical, I just solved them.
S40	...#1, 2, 3, 4, because there is only basic math.

4.2 Mathematical procedures: answers vs solutions

The comparison of the answers to questions Q2 and Q3 with students' solutions showed that students performed worse when solving a ratio problem within the T3 task (which they identified as a mathematical task) than when solving the other tasks (which they pertained to chemistry). One eighth of the respondents solved T3 incorrectly (with 7000 ml as the result), but T4 correctly. In these cases, the solution procedures to the correctly solved chemistry-labelled tasks were usually based on algorithmic procedures learnt in chemistry lessons.

Students who were able to include the mathematical concept of ratios when solving the chemistry-labelled tasks, were also among those who mentioned advantages when responding to the question Q7. However, not much detail appeared in these responses (see Table 6). An interesting answer (S40) was that in all problems, a combination of mathematics and chemistry could be used, which would then provide more options for their solution.

Table 6. Students' reactions to Q7 – the advantages of combining mathematics and chemistry

Student code	Reactions to Q7
S07	I guess so at 2, 5, 6. I think it has its advantages.
S22	Yes, 2, 5, 6. The advantage is that I can use the ratio to find the element I'm looking for.
S20	5. I used the ratio between the molar masses and calculated how much calcium, and oxygen would be formed from calcium oxide.
S33	For example, in 5, 6, I used the rule of three. It can be combined.
S40	Yes, in all of them. Multiple solutions to the task.

Discussion and conclusions

In our study, we prepared a worksheet with six tasks to solve and seven groups of questions to answer to address the research question *Are the students able to identify mathematical topics included in the tasks and are they aware of the possibility to apply mathematical procedures when solving them?* From a content perspective, we focused on the mathematical topic of ratios and its chemical applications within the stoichiometry topic. According to Stohlmann (2019), we fulfilled the condition of at least two disciplines involved, thus we could consider our tasks as STEM tasks. The worksheet also included questions for student self-reflection. We used similar principles as Anggraeni et al. (2022). The study revealed that the students mostly perceived the subjects of mathematics and chemistry as distinct and tended to perceive problems with chemistry terms in the assignment as purely related to chemistry even if mathematical content was included in them and mathematical procedures could be used to solve them. As in (Honey et al., 2014), the majority of students were not able to apply mathematical procedures when solving chemistry problems, as they saw these procedures as something they had learnt in another school subject rather than the subject in which the assignment of the task was given.

The tasks indicated that chemistry was prioritised while mathematics was largely neglected. Consistent with the findings of Ramful and Narod (2014), students struggled to transfer their knowledge of ratios from mathematics to the context of chemistry. Moreover, some students were able to solve the ratio-related chemistry problem (task T4) but not the ratio-related problem with a mathematical assignment (task T3; similar problems are frequent in mathematics textbooks on ratios). Such findings supplement those of Gabel et al. (1984): their secondary school students were able to perform algorithms learnt in chemistry lessons, despite apparent lack of conceptual comprehension; this was attributed to the procedural knowledge they had acquired. In these cases, conceptual comprehension might be lacking not only in chemistry but also during the transfer from mathematics to chemistry. To enhance their performance with similar cross-curricular tasks, it seems that students without STEM experience need to perceive the possibility of applying the mathematical procedures they have learnt in mathematics when solving the chemical problem; such an approach might also give them the impression that mathematics is meaningful (Fitzallen, 2015). The tasks in our worksheet seem to be a good starting point for these activities; the respondents could benefit from being encouraged to apply mathematical procedures also outside of mathematics.

Although the assignment of the tasks in the worksheet could unconsciously or unintentionally lead students to consider the tasks associated with a single discipline, and so trigger affective domain barriers related to the discipline (as e.g. in Ross et al., 2018), there were also students who were able to see the tasks as integrated and independent of a specific discipline (Table 6). We will focus on this aspect in more detail in our future work. Furthermore, we will also investigate what effect on students' preferences in solution procedures could have a change in the data collection environment from chemistry to mathematical lessons or from standard lessons to a problem-based learning context.

The limitations of the study are the same as those of all qualitative studies. The results cannot be generalised and are tied to a context-specific case. Respondents with different contextual backgrounds may respond differently.

Acknowledgements

This article was supported by the *Grant Agency of the University of South Bohemia in České Budějovice, under the project no. 041/2022/S* named *Key areas of the curriculum for the integration of educational content in the field of STEM.*

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