Koerfer *et al.*
Disciplinary and Interdisciplinary Science Education Research (2025) 7:15
https://doi.org/10.1186/s43031-025-00135-x

Disciplinary
and Interdisciplinary Science
Education Research

RESEARCH Open Access

Teachers' conceptions of the role of mathematics in STEM higher education

Ebba Koerfer[1*], Giulia Polverini[1], Maja Elmgren[2], Lars-Henrik Eriksson[3], Lisa Freyhult[1], Roger B. Herbert[4], Felix M. Ho[2], Andreas Solders[1] and Anna Eckerdal[3]

Abstract
This empirical study investigates university teachers' conceptions of the role of mathematics within science, technology, engineering, and mathematics (STEM) higher education disciplines, employing a phenomenographic approach to capture variation among perspectives of educators in chemistry, computer science, geoscience, and physics. Despite the significant reliance on mathematics across these disciplines, little is known about how educators conceptualise its role. Our study aims to contribute to this research by performing a phenomenographic analysis of semi-structured interviews with 16 teachers at a Swedish university. Through our analysis, we identified five hierarchically inclusive categories that represent increasingly sophisticated conceptions of the role of mathematics: as a computational tool, a language for communication, a key to understanding, an agent for development, and a philosophical foundation. These categories reflect both the instrumental and intrinsic roles that mathematics plays within other STEM disciplines, extending previous empirical findings that predominantly focus on students' conceptions. We aim to raise awareness among educators, encouraging reflection on how their conceptions influence teaching and fostering a deliberate consideration of mathematics' role in instruction. By understanding these varied conceptions, STEM educators can enhance instructional strategies and support student engagement with mathematics in a more meaningful way.

Keywords STEM higher education, Role of mathematics, University teachers, Phenomenography, Semi-structured interviews

Introduction

Students' challenges in mathematics are a well-known reason for dropouts in STEM education (Kussuda & Nardi, 2019). Previous research has established the importance of students' and teachers' conceptions of the role of mathematics in STEM areas. How teachers conceptualise mathematics has an impact on their teaching and thus students' learning (Uhden et al., 2012; de Ataíde & Greca, 2013). For example, Hofer (2001) argues that teachers' epistemic beliefs shape their classroom practises, which in turn influences students' ideas about knowledge and knowing, their study approaches, and ultimately, the learning outcome. Students' difficulties with mathematics in science and engineering, especially

*Correspondence:
Ebba Koerfer
ebba.koerfer@physics.uu.se
[1]Department of Physics and Astronomy, Uppsala University, Box 516, Uppsala 751 20, Sweden
[2]Department of Chemistry – Ångström Laboratory, Uppsala University, Box 523, Uppsala 751 20, Sweden
[3]Department of Information Technology, Uppsala University, Box 337, Uppsala 751 05, Sweden
[4]Department of Earth Sciences, Uppsala University, Villavägen 16, Uppsala 752 36, Sweden

Springer Open

© The Author(s) 2025. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/.

physics, are well-documented. Success in mathematics courses alone does not guarantee effective problem-solving abilities in the contexts of other disciplines, in part due to the integration of rich physical meaning in mathematical expressions and representations (Uhden et al., 2012). By contrast, much less is known about how university teachers in science and engineering themselves view mathematics within their disciplines. This can influence and shape both their expectations about what students should learn and whether teachers perceive a need for explicit and directed instruction to support student learning to use mathematics contextualised within their disciplines. These aspects could also ultimately influence how they design, approach and implement their teaching activities.

This study addresses this gap in the research by exploring university teachers' conceptions of the role of mathematics within the knowledge structure of various STEM disciplines. Given that teachers' views play a central role in shaping students' understanding and use of mathematics, understanding these conceptions is critical for identifying potential mismatches in teachers' perspectives on mathematics and their instructional strategies. Our aim is to contribute to the empirical groundwork by increasing awareness among educators, helping them to reflect on how mathematics is positioned in their teaching according to their conceptions. While most existing research in the area is theoretical and comes from physics education research (e.g., Uhden et al., 2012), this article takes a broader view and investigates several STEM disciplines where contextualised use of mathematics is common yet challenging for students. The goal is not to compare and contrast different disciplines, but to paint a broader picture of mathematics' role in STEM higher education. Our research question is:

> *RQ* What are university teachers' conceptions of the role of mathematics within the knowledge structure of other STEM disciplines?

To this end, we take a phenomenographic approach, suitable for investigating qualitatively different variations in the conceptions of a phenomenon among a group of people (see Sect. Theoretical framework and methodology).

Related work

A considerable body of research examines the relationship between mathematics and science, especially concerning physics. Some take a historical or philosophical perspective (see e.g., Tzanakis & Thomaidis, 2000; Quale, 2011; Branchetti et al., 2019), while others focus on the teaching and learning of this relationship (see e.g., Lutz & Srogi, 2000; Paulson, 2002; Olafson & Schraw, 2006; Tuminaro & Redish, 2007; Redish & Kuo, 2015; Maass et al., 2019; Karam et al., 2019; Krey, 2019; Palmgren & Rasa, 2024). Most research in the latter category agrees that students' views on the role of mathematics in science influence their learning (Redish & Kuo, 2015; Greca & de Ataíde, 2019; Karam et al., 2019). Further, Uhden et al. (2012) found that "… proficiency in mathematics does not guarantee success in physics." There is thus ample literature supporting the view that contextualised mathematics is significantly different from mathematics in isolation. Distinguishing between mathematics as a tool and mathematics as a (conscious) generalisation has been highlighted as an important theme within interdisciplinary mathematics education (see e.g., Doig et al., 2019; Dreyfus et al., 2023; Goos et al., 2023; Stillman et al., 2024). A recent review by Kristensen et al. (2024) examined the role played by mathematics in STEM teaching activities found in various studies. They proposed a framework consisting of two major categories: mathematics utilised as a tool or mathematics as the aim of the activity, for a few different purposes each.

An example of exploring the relationship between mathematics and physics is the analytical framework by de Ataíde and Greca (2013), which classifies conceptions of mathematics as a mere calculation tool, a translator of physical processes into symbolic representation, or an integral and structural part of the discipline. This echoes the characterisation of roles by Palmgren and Rasa (2024). The same idea was previously proposed by Tzanakis and Thomaidis (2000), who describe the dichotomy between mathematics and physics as a potential impoverishment and trivialisation of not only the relationship between the two disciplines, but also of the disciplines per se: "mathematics is merely a tool to describe and calculate, whereas, […] physics is only a possible context for applying mathematics previously conceived abstractly" (p. 49). Uhden et al. (2012) have also discussed and distinguished between mathematics playing a *structural* role in physics, being an inseparable part of the knowledge structure of the discipline, from a purely *technical* role in mathematical manipulations.

While less well-researched, similar issues have also been identified for the role of mathematics in chemistry, gaining attention in the chemistry education literature (Bain et al., 2019; Towns et al., 2019; Ye et al., 2024, 2025). In a range of areas in chemistry, mathematics plays a key role in how chemical phenomena are described, modelled and analysed. Importantly, not only is technical proficiency in mathematics needed for performing necessary mathematical operations, a range of chemical and other non-mathematical resources also need to be activated and appropriately employed for productive model construction, and even in guiding how mathematical work should proceed. This has been discussed by Ho et al.

(2019), Ye et al. (2024), and Ye et al. (2025) in the context of mathematical modelling in chemistry.

From computer science, Beaubouef (2002) contends that mathematics is deeply intertwined with the study of computer science, from its most basic courses through to the most advanced. The intrinsic connection of computer science to mathematics is also suggested by Knuth (1974) who defines computer science as a branch of mathematics because similar to mathematics, it addresses human-devised principles that can be deductively proven. Wilson and Shrock (2001) found that a mathematics background is one of three statistically significant factors predicting success in an introductory computer science course. Baldwin et al. (2013) considers mathematics as a framework for reasoning about computing and computer science as well as for solving problems and developing problem-solving skills. Given the central connection, both on a conceptual and practical level, in terms of providing skills and tools, the role mathematics plays in computer science education is problematised and discussed. Henderson (2005) describes mathematics to be a natural complementary discipline to computer science and software engineering which enables the understanding of many fundamental computational science problems, arguing that graduates of mathematically focused programs will become better computer scientists and practicing software engineers. de Almeida et al. (2023) compared students' results from a first programming course and a course in Differential and Integral Calculus and found a moderate correlation. The authors conclude that learning programming requires not only reinforcement of fundamental mathematical concepts but also the cultivation of logical reasoning and problem-solving skills.

Within geosciences, Lutz and Srogi (2000) discuss teachers' insights on students struggling with mathematics and its perceived irrelevance within the subject. Macdonald and Bailey (2000) argue that the geosciences in the last century have changed from being dominantly descriptive to being more quantitative, i.e., more mathematical. They suggest a matrix approach to identify the quantitative skills relevant to a geology curriculum, and to analyse how these skills are integrated. In a similar manner, Manduca et al. (2008) and Wenner et al. (2009) argue for the need for more emphasis on quantitative literacy, to be able to understand and use numerical information in real world problems, in geoscience education. Wenner et al. (2009) more specifically outline different approaches drawn from mathematics education to improve teaching quantitative literacy in geoscience curricula.

There has been some research exploring the connection between teachers' beliefs about teaching and learning and their instructional practices (e.g., Gibbons et al., 2018; Popova et al., 2020). There also exists some research on school teachers' views on the role of mathematics in science, showing that the way they are communicated can influence pedagogical choices and therefore also what and how students learn (e.g., Redfors et al., 2016; Pospiech et al., 2019a, b). For example, Pospiech et al. (2019a) reported a variety of views and strategies among school teachers in physics. Particularly prevalent was the view of mathematics as a tool or instrument in physics, but also a recognition of mathematics as contributing to the understanding of physics. Pospiech et al. (2019a) also conclude that despite some of the school teachers' theoretical awareness of the structural role of mathematics, this tended to be less visible in their everyday teaching due to e.g., the teachers' perception of students' abilities. However, a specific relationship between the teachers' views of the role of mathematics in physics and their teaching strategies could not be confirmed and remains an important area to explore. Moreover, little is known about how university teachers and students conceptualise the nature and role of mathematics in the knowledge structure of other STEM disciplines. This includes whether they are explicitly aware of the additional layers of epistemic complexity (Bing & Redish, 2009) involved in the encoding of physical information and the nature of mathematical equations and representations when contextualised in another discipline. More previous research argues that teachers' views have implications for teaching and thus learning (Uhden et al. 2012). For example, de Ataíde and Greca (2013) claim that if the relationship between physics and mathematics is not clear to teachers, "it is quite likely that students will also fail to grasp their true nature and will assume a naive attitude; believing that they need know no more than the equation and its solution to solve problems in physics" (p. 1406). Whether, and to which degree, teachers' and students' conceptions match or mismatch has not been researched either.

Theoretical framework and methodology

This project is theoretically anchored in the phenomenographic tradition (Marton & Booth, 1997; Marton et al., 2004; Marton, 2014). Phenomenography has frequently been used in STEM higher education to study students' conceptions of discipline-specific central phenomena (Eckerdal et al., 2024; Koballa et al., 2000; Marshall & Linder, 2005; Trigwell, 2006), and some studies have also focused on educators' experiences of teaching and learning within their disciplines (Berglund et al., 2009; Ingerman & Booth, 2003; Prosser et al., 1994).

Phenomenography is a qualitative, empirically based research approach specifically developed for educational research. Traditionally, it is used to explore the variation

in how people experience or understand[1] a phenomenon, often a central concept. At the heart of the approach "lies an interest in describing the phenomena in the world as others see them, and in revealing and describing the variation therein, especially in an educational context" (Marton & Booth, 1997, p. 111). Central to the tradition is the idea that differences in understanding imply varying degrees of complexity or sophistication, and that learning involves becoming aware of new aspects or relationships within a phenomenon. The result of a phenomenographic study is a set of categories describing the different ways a group of people could understand the phenomenon. These categories can be hierarchically ordered to reflect increasingly complex conceptualisations. The focus is on the collective understandings rather than individual voices; the aim is to identify qualitatively distinct ways of experiencing, not to represent every individual's view (Marton & Booth, 1997). This collective perspective is essential for highlighting shared patterns and variations within a defined group[2].

Phenomenography aligns with broader qualitative research traditions. It resonates with Carminati's (2018) account of qualitative research, where the goal is to provide rich explanations and deep insights rather than to generalise findings statistically. This approach is particularly suited for exploring complex social phenomena as experienced by people, aiming for a deeper and more meaningful understanding. Data collection typically involves in-depth interviews with open-ended questions, allowing for follow-up questions and clarifications. This semi-structured format supports deep exploration of participants' experiences and can yield rich, nuanced data. In line with this aim, sampling and context play a critical role. It is important to select the group of people with care, and describe relevant characteristics, as well as the context of the interviews, so that the reader can infer whether the results of the study are transferable to their own context. Transferability is often discussed as corresponding to the concept of generalisability in the quantitative research paradigm (Lincoln & Guba, 1985). Carminati (2018) also notes that determining an adequate sample size in qualitative research depends on the quality of data and appropriateness of the method, not on numeric thresholds. This aligns with the phenomenographic approach, where the focus is on capturing the variation in experiences rather than achieving statistical generalisability. The goal is to identify qualitatively different conceptions within a group, and an appropriate sample size is reached when further data collection no longer yields new, distinct ways of understanding the phenomenon. However, within this framework, there is no claim to have captured all possible conceptions that any individual might hold; rather, the aim is to represent the range of variation present within the studied group.

The analytical process also follows the principles of variation. During a phenomenographic analysis of interview data, researchers iteratively compare and group quotes based on shared meanings or ways of understanding the phenomenon. There are often several researchers involved in different stages of the analysis to strengthen the trustworthiness of the results by bringing in diverse perspectives and reducing individual bias. The resulting categories are the researchers' representations of possible qualitatively different conceptions based on the data, each category illustrating aspects of the phenomenon which some learners may have discerned but others have not. The result of the analysis is typically an outcome space with categories labelled and described in detail to highlight its distinctive features and relationships between them. Illustrative quotes exemplify each category and enhance transparency. The categories often form a hierarchy, reflecting increasingly complex or advanced ways of understanding the phenomenon. This hierarchy aligns with phenomenography's view that learning involves progressing toward more developed conceptualisations. Conducting such analysis requires researchers with disciplinary expertise to accurately interpret participants' descriptions, discern subtle differences in conceptions, and ensure that the categories capture meaningful distinctions within the relevant context.

To better understand the theoretical underpinnings of this approach, it is helpful to consider how variation theory has emerged in close connection with, and as a development of, phenomenography. Already in 1997, Marton and Booth started to formulate a theory of awareness and learning in their seminal work Learning and Awareness. The book discusses variation in terms of what aspects of a phenomenon people are simultaneously aware of. As the theory developed, yet another aspect of variation came to the fore, sometimes referred to as "the new phenomenography". The focus shifted to discuss variation as a necessary, if not sufficient, condition for learning. To become aware of a new aspect of a phenomenon, the learner needs to experience variation in that aspect. This idea was further developed into variation theory of learning in later work by Marton and other researchers (Marton et al., 2004; Marton, 2014).

Consequently, phenomenography and variation theory are closely intertwined. Åkerlind (2018) suggests that phenomenography and variation theory research are inherently intertwined research approaches, and they share a common theoretical framework including

[1] Experiencing and understanding is often used interchangeable in the phenomenographic literature.

[2] Phenomenography, with its focus on exploration of *variations* in experiences or understanding within a group, should not be confused with phenomeno*logy*, which focuses more on the essence of lived experiences of individuals to understand the core meaning of a phenomenon.

underlying epistemological and ontological assumptions. Booth reinforces this connection by nothing that "… phenomenography and variation theory have been employed as methodological and theoretical frameworks to study different aspects of learning and the context for learning, in terms of qualitative differences across a cohort of students." (Booth, 2008, p. 455).

In this light, the present project draws on this shared theoretical foundation – understanding phenomenography not merely as a method but also as part of a broader framework for analysing how variation in awareness shapes learning.

The study

Our project aligns with the phenomenographic methodology, as presented in Sect. Theoretical framework and methodology, focusing on a central phenomenon: the role of mathematics in STEM higher education from the teachers' point of view.

Students in STEM programs normally take courses from several disciplines. In pure mathematics courses, they encounter concepts that they are supposed to use and implement in several areas of other disciplines. We are thus interested in investigating how teachers in disciplines other than pure mathematics conceptualise the role of mathematics in their respective disciplines. The goal is to identify conceptions among educators from these disciplines as a group, not differences between disciplines or individuals, in line with the phenomenographic tradition (Marton & Booth, 1997).

Table 1 Background and pseudonymised abbreviations of the interviewees

Discipline	Interviewee abbreviation	Subdiscipline	Years of teaching	Years of doing research
Chemistry	Ch1	Molecular biotechnology	> 10	> 10
	Ch2	Organic chemistry	> 10	> 10
	Ch3	Material chemistry	> 10	> 10
	Ch4	Physical chemistry	> 10	> 10
Computer Science	CS1	Programming languages	> 10	> 10
	CS2	Theoretical computer science	> 10	> 10
Geoscience	Ge1	Water engineering	> 10	> 10
	Ge2	Geohydrology	> 10	> 10
Physics	Ph1	Astro- and stellar physics	< 5	5–10
	Ph2	Physics education research	> 10	> 10
	Ph3	Theoretical physics	> 10	> 10
	Ph4	Particle physics	> 10	> 10
	Ph5	High energy physics	< 5	< 5
	Ph6	Materials theory	> 10	> 10
	Ph7	Nuclear physics	> 10	> 10
	Ph8	Biophysics	> 10	> 10

As a first step, we conducted a pilot study with the aim of constructing semi-structured interview questions and gauging the consistency of teachers' views on the role of mathematics across the disciplines. Eight pilot interviews were performed, where the authors took turns interviewing each other using a set of tentative questions. The interviews were transcribed and each author reviewed all transcripts, marking relevant quotes to the phenomena, and suggesting initial categories. The quotes were then revisited and fitted into categories, a process that included identifying missing or redundant categories. The final categories were shared and agreed upon by the group. In this pilot study, we found clear similarities in the expressed conceptions of the role of mathematics across the disciplines, supporting the decision to conduct a full phenomenographic study with teachers from the four disciplines.

The interview questions from the pilot study were modified to be less abstract and probe more aspects of the interviewees' conceptions of mathematics within their discipline. Subsequently, we used the mutually agreed upon interview guide (see Supplementary Material) to perform interviews with a total of 16 teachers (11 men, 5 women) from chemistry, computer science, geoscience, and physics at a large Swedish university. We deliberately chose more experienced teachers, as their reflective insight increases the likelihood of capturing a broad range of conceptions – from basic to more developed – which aligns with the phenomenographic aim of identifying variation within a phenomenon. This number of participants is consistent with established practice in phenomenographic research, where the aim is to capture a range of qualitatively different ways of understanding a phenomenon rather than to achieve statistical representativeness.

The use of mathematics varies between and within different disciplines and the interviewees were therefore selected to represent this variety (see Table 1). Each researcher interviewed two teachers from their own discipline to ensure that the interviewer had enough disciplinary knowledge to be able to ask relevant follow-up questions. Based on language proficiency, six interviews were conducted in Swedish and ten in English; the transcripts in Swedish were later translated into English. Participation was voluntary and the teachers signed a written consent form with information about the study. Each interview was planned to be approximately 30 min;

however, the actual length varied between 15 and 50 min. Each interviewer started by asking the participant to give some background in terms of their field of study and their experience (Table 1). To reduce bias, interviewers encouraged elaboration, asked follow-up questions, and invited participants to reflect on colleagues' views as well as their own. We recorded and transcribed all interviews. All raw and processed data were uploaded to a safe server provided by the university, and the files were erased from the recording devices.

The transcripts of all interviews were analysed by each researcher, following the same methodology as for the pilot interviews. Namely, after reading all the transcripts, quotes found relevant to the phenomenon were marked and then a tentative set of categories was made. The quotes were then revisited and placed into the categories, identifying any redundant or missing categories. Following individual analysis, the researchers split into two groups: one with four researchers in physics, and the other with two researchers in chemistry, one in computer science, and one in geoscience. Each group discussed and consolidated their proposals into one set of categories, resulting in two slightly different sets of categories. In the end, the categories with corresponding quotes were compared and discussed among all researchers until a consensus was reached on one single set of categories and their descriptions. Finally, representative quotes were selected to illustrate each category constituting the outcome space.

Findings

In the following sections, we present the findings from the analysis of the interviews as an outcome space. We identified five categories of qualitatively different ways of conceptualising the role of mathematics in STEM higher education, from a teacher's perspective. The outcome space is hierarchically inclusive, which means that the categories are increasingly broad since each category includes the features of all previous ones, in addition to its own. We elaborate on the hierarchy of the outcome space in Sect. Hierarchy of the categories. In Table 2, we describe the categories and provide representative quotes from the interviews. Note that the outcome space describes the researchers' representation of conceptions on a collective level, not individuals' conceptions.

A computational tool

The first category summarizes the conception that mathematics assumes the role of a tool for calculations in the discipline, which can have different degrees of complexity according to the context. Within this interpretation, mathematics (i.e., formulas, rules) is applied in a simplified and mechanical way, which neither requires a deep understanding of mathematical principles nor increases the understanding of the discipline. A few more illustrative quotes, in addition to those in Table 2, are given below.

> *Yeh, eh, astrophysics is very broad... so... for a particular problem... a particular mathematical tool*

Table 2 An outcome space of teachers' conceptions of the role of mathematics in STEM higher education. The outcome space is hierarchically inclusive (e.g., category 3 also includes the features of categories 2 and 1)

Categories	Descriptions	Representative quotes
1. A computational tool	The role of mathematics in the discipline is conceptualised as a tool for calculations.	*"Very often we want to make some type of calculations when we have to solve various problems in hydrogeology, then mathematics is needed as a tool for these calculations." Ge2*
2. A language for communication	In addition, the role of mathematics in the discipline is conceptualised as a language to describe, formulate and explain.	*"But the second thing which is also maybe equally important is that it gives us a common language to talk about this topic which can be quite abstract. It gives us way to talk about data structures and algorithms and their complexity and these things. So the it's it's it's a common language that that we can all understand…" CS1*
3. A key to understanding	In addition, the role of mathematics in the discipline is conceptualised as something fundamental to understanding the discipline. In this sense, mathematics is a key to reasoning, finding relationships, drawing conclusions, providing structure and modelling.	*"Yes indeed, and I think you get a bit, both a bit deeper but also a greater understanding of systems if you have the mathematics. I usually say I have a mathematical mind but I don't. But I usually instead look at the complexity and understand dependencies and how parts are dependent on each other. Even in societal systems." Ch1*
4. An agent for development	In addition, the role of mathematics in the discipline is conceptualised as a vehicle to develop the discipline, formulate new questions and drive research forward.	*"So that, there is a physics without mathematics but that is not able… that does not allow you… to… to do physics research, to put physics forward, right? It's only as you can use it for the state of the art, okay? Because then you have understood it, right? But if you want to drive it forward, if you want to… to evolve it, then mathematics is completely necessary." Ph6*
5. A philosophical foundation	In addition, the role of mathematics in the discipline is conceptualised as an inherent part of the knowledge structure. In this sense, mathematics is experienced as a philosophical foundation since it is not simply utilized for a purpose within the discipline, but it is how the discipline functions.	[Due to the intricate and multifaceted nature of this category, we refer to the main text where the representative quotes are provided with sufficient context.]

might be needed… I think in practice you encounter some problem and then you need some maths to solve it… I will go in for example revise the mathematics or maybe learn the mathematics from a textbook that I need to solve that problem. Ph1

Well, you need to have a basic understanding of the, yeah, how the equations work. It's good that you know something about differential equations, but I would say that's not really necessary if you were to apply the tool, of course when you want to make modifications and adapt the tool to your particular problem it's helpful that you have a basic understanding of mathematics. Ge1

You know, sometimes you don't care about understanding. You want a certain, you want a certain value to use in another experiment or something so I don't really wanna engage with it too much you trust that someone who has, you know, derived or found this relationship or devised this model has done a good job. Ph2

A language for communication

In the second category, in addition to the features in the previous category, the conception of mathematics as a universal language is highlighted. Mathematics is conceptualised as a means to communicate the content of the discipline in a formal way, for example:

I would say it is a language in which we express the world around us, the processes that are occurring in hydrology or in water engineering so this is a universal way to communicate what we mean the processes. Ge1

I see mathematics as a way to explain different processes that exist in all these different subjects. Biology, chemistry, physics, IT of course, biophysics, bioinformatics. Ch1

This category, like the previous one, does not imply that mathematics is necessary for a deep understanding of the discipline. However, mathematics assumes a broader role than just as a computational tool, since it allows the translation of the content into a formalism everyone can interpret, namely describing and explaining disciplinary knowledge using mathematical notation. We provide an example below where conceptions from the first and second categories are present, where the features of the second category are highlighted (bold font):

*… it is important not only to be able to **explain** something in mathematical terms, but also precisely to be able to read, without having the equation, that is, without being able to **explain** connections qualitatively as well, just as students should not only be able to let us say count, but they should be able to **describe** what they have actually done when they have calculated or **described** a model or something else. Ch4*

A key to understanding

The third category brings out the conception of the role of mathematics as fundamental to the discipline. Mathematics is conceptualised as necessary to gain a deep understanding of the discipline, since it provides a structure for reasoning and the ability to find connections between concepts. Moreover, it is required for constructing models in the discipline, making predictions, and drawing conclusions.

Such that, then it is a form of, in its own way, there are different types of understanding here. Because, I think that in order to really reach a real deep understanding of a physical phenomenon, then you have to have this mathematics. You have to go deep, you have to see all the details, in order to really understand what is happening. Ph3

And that gives you then … only the mathematics gives the possibility to come to conclusions. Ph6

Again, this category includes the features of the two previous ones, but extends them by adding the conception that mathematics is essential for understanding the discipline (highlighted in bold font). For example:

*… It's easy to think of mathematics as a tool [for calculation] because that's what, that's how it is used sometimes. But in physics it's more than that because it really gives you a way of **reasoning** about phenomena, it's not just for calculating so you can **reason** with mathematics … Ph2*

*It's a language, you could say. That's how you can specify and formulate the understanding of the world around us, when it comes to physics and natural sciences, and perhaps other things as well. But especially in physics. So it's a language to describe, but it's also a language that you can use **to reason and come to conclusions**. Ch4*

I would say it is it is comparable to language if we talk about the command of language that we would want to express things in words or in mathematical

symbols symbols yeah so it 's like a key to understanding. […] We add a level of abstraction to it, we assign… yeah we describe relationships between different factors … Ge1

But there are many areas where mathematics is very central and is ***absolutely needed to understand the concepts*** *and the things we are talking about. And yeah, so it depends a little, but it's difficult to see a computer science degree without mathematics. CS2*

An agent for development

The fourth category reflects the conception that mathematics is crucial, not solely to understand the discipline, but also to develop it beyond its current state. The role of mathematics is conceptualised as a means to advance the discipline by generating new research questions and expanding the disciplinary knowledge.

I think [understanding mathematics in the subject] opens up like new possibilities, and so I think it develops our brains to… Through our conceptual thinking in itself then, can still see so much more nuances, and be able to see more components of the systems that we're working with. Ch1

After all, mathematics is crucial to being able to acquire advanced chemistry within a great many of the disciplines in any case. Ch3

Especially this work […] that I do. I mean, that's, that's all about applying logic, mathematical logic, in order to evaluate ideas and get results out of them. CS1

We also provide a few examples of quotes including features from the previous three categories, as well as the new conceptions from this category (bold font):

So that mathematics is extremely important to be able to ***develop*** *the explanatory models, because it is mathematics that is the language that we use. It is the language that we use for our models in the natural sciences. So if you want* ***more complex models****, it can lead to more complex or more difficult mathematical problems. Ch4*

So mathematics can both explain it [different processes], but can also ***increase understanding and move the questions forward****, within these different subjects, you can use mathematics to* ***gain knowledge*** *that you can* ***ask new questions*** *that need to be* ***developed and researched****. So it is both that you use it to understand what you have, but also that you use it to be able to* ***predict how to proceed****. Ch1*

A philosophical foundation

In the final emerged category, the disciplinary knowledge is conceptualised as inherently mathematically structured. This category implicitly includes the four previous ones, and presents a higher level of sophistication because the role of mathematics in the discipline assumes an increased integral role and embraces a more philosophical perspective. There may be several possible positions regarding the philosophical conception of mathematics in the discipline. In one case, the discipline is seen as almost synonymous with mathematics.

So I mean research-wise I work in theoretical computer science which is perhaps closest to mathematics. So I think theoretical computer science in a way is mathematics, only on slightly different topics and concepts. We use the same tools and methods, we have proofs, we have mathematical reasoning. So much of that is very similar to what mathematicians do. CS2

The following quotes illustrate two different philosophical positions. Mathematics can be seen as an "entity" that exists in our universe, a part of reality, and therefore an absolute truth. This conception was, however, neither shared nor encouraged by the interviewee. Rather, it was described as a conception that they previously had, and that some colleagues and famous spokespersons for science still have, for example:

Yes, I can imagine that in the beginning maybe, when I was younger, I possibly had a more naive and more platonic attitude. Possibly like that, that I thought that this mathematics might be something that floated together with the laws of nature above the world and so on. Eh, and there are many who still, who have have that perception too, even though they have been working on these things for a long time. Ph3

The interviewee distances themself from this philosophical position and points out their reasons. This conception was presented as possibly misleading, and even dangerous, as argued in the following quotes:

I think there is a risk there that you get misled a little bit. That you imagine that the universe must align itself according to certain principles. That you get the idea that since mathematics is often associ-

ated with some form of beauty and elegance and such things, then you have to imagine that the universe must respect the same principle of simplicity in some way, right. […] But, but I think that essentially, it's about a limited point of view, which means that you can miss certain important aspects of the world. That you choose to see the world in a certain way, which rather reflects one's own prejudices than something real out there. Ph3

… If you put an equal sign between the physical model and some form of absolute mathematics, which additionally exists regardless of us, then you can be limited. It becomes such that you, you don't question it as much as if you actually realize that this is a mathematical model, a model based on mathematics. Which in turn is a tool and a language, and nothing else. Ph3

[someone's perception of the role of maths in their subject can affect their approach to it and the research] and maybe more than that actually. It can even be that this desire for the independent existence of mathematics, and all this, it connects a bit further to our obsession with virtual worlds really. Where our entire society begins to live in some kind of world of algorithms, where we lose contact with the physical, real world. So that, I think it goes even deeper than that. I think it can even be dangerous to believe in the independence of mathematics, it's not as innocently philosophical as you might think. Ph3

These quotes demonstrate the complexity of the final category of conceptions, where mathematics assumes a highly integral role in the discipline, and touches upon potential epistemological issues related to a blurred line between mathematics and the discipline.

Hierarchy of the categories

As described in the overview of the different categories, the outcome space is hierarchically inclusive in the sense that each new category includes the features of all previous ones, in addition to its own. In this regard, the categories are increasingly broad. This inclusive nature of the outcome space is illustrated in Fig. 1. In addition to breadth, it can be seen in our findings that there are increasingly sophisticated conceptions of the role of mathematics moving across the five categories, in the sense of more and more nuanced and complex conceptions of the relationship between mathematics and the discipline.

The first category represents the most basic conception, with mathematics essentially being regarded as a computational tool to be used in the other discipline, often applied in a simplified and mechanical way (e.g., like a "black box"). Within this category, mathematics is not conceptualised as, for example, a means to communicate or increase the understanding of the discipline. The second category also recognises mathematics as a tool for calculations, but advances the conception to include the communicative role of mathematics in the discipline. Mathematics is regarded as a means to communicate through a translation of the disciplinary content into a formalism everyone can interpret, i.e., describing and explaining disciplinary knowledge using mathematical notation. However, this conception does not imply that mathematics is necessary for gaining a deep understanding of the discipline. This is what differentiates the second and third category. The third category describes mathematics as crucial for a deep understanding of the discipline, beyond (and including) both computation and communication, and is therefore considered higher and broader in the hierarchy. The fourth category encompasses all previous roles while advancing the conception further by considering mathematics as a means to advance the discipline by generating new research questions and expanding the disciplinary knowledge. The qualitative difference between the third and fourth category is that mathematics is crucial not just to understand the discipline, but also to develop it beyond its current state. Finally, the fifth category presents the broadest and most sophisticated conception. It describes the highly integral role of mathematics as connected to the underpinning functions of the discipline. It also differs from the previous conceptions by introducing philosophical positions about the very nature of the discipline itself with respect to mathematics. Within this conception, since mathematics is intertwined with the discipline, it plays a role in all the purposes described in the previous categories. For example, mathematics is consequently employed in reasoning and gaining a deep understanding within the discipline, since it is an inherent part of the discipline, and so on.

To summarize the overarching trends, we note that mathematics starts from a general instrumental role in the first category, then becomes decreasingly instrumental and increasingly integral to the other discipline, to finally being considered as intertwined with the discipline at its core. Consequently, the latter categories provide more potential to capture nuances in the role of mathematics and how these various roles are connected.

Discussion

The roles of mathematics in other STEM disciplines have been explored through various perspectives, including historical (Quale, 2011; Branchetti et al., 2019), philosophical (Uhden et al., 2012; Steiner, 2009), and semantics analysis of its language (Redish & Gupta, 2009).

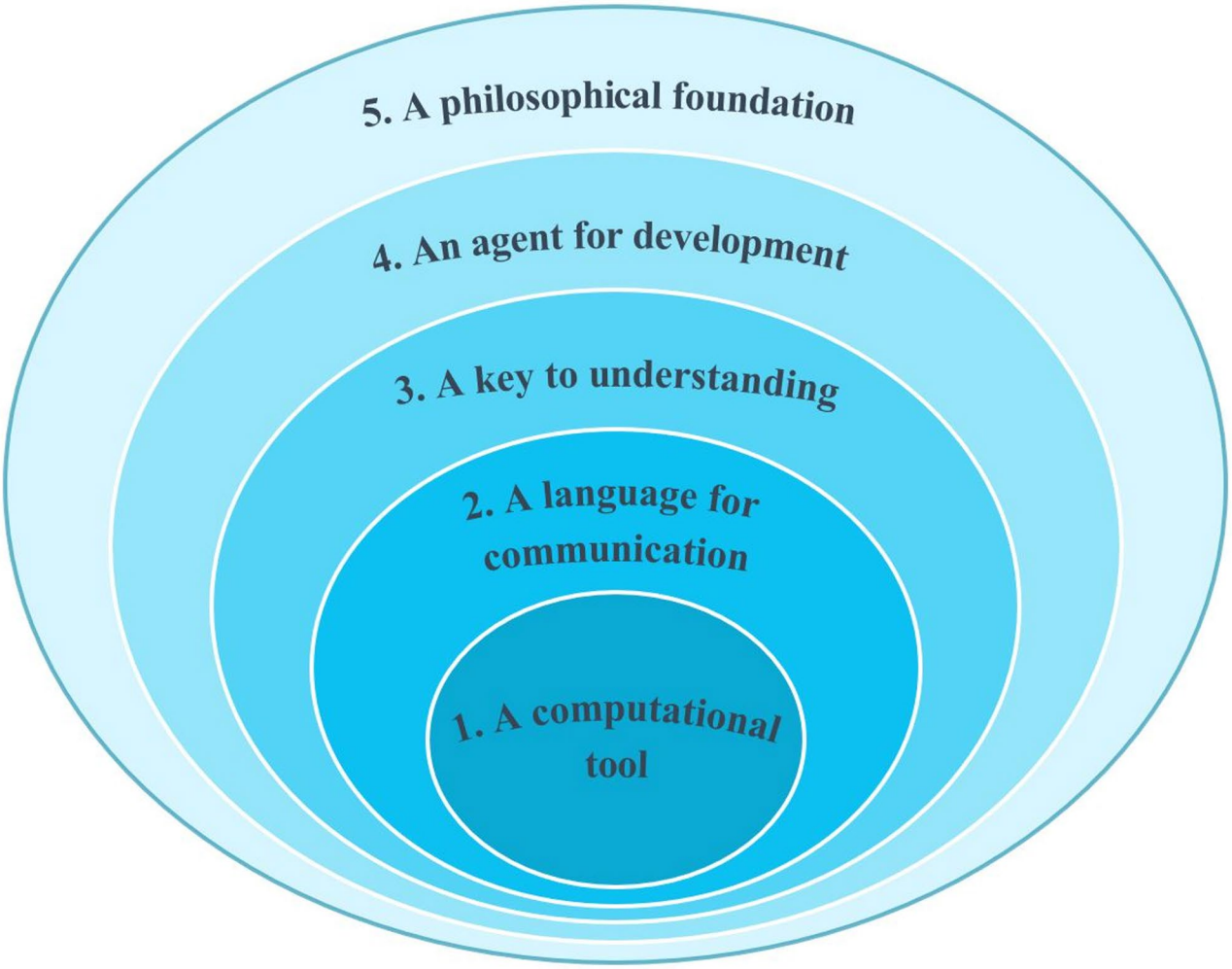

Fig. 1 A visual representation of the outcome space, illustrating the hierarchical relationships between the categories described in the main text

Additionally, research has examined students' cognitive processes (Blum & Leiss, 2005), school teachers' views (e.g., Pospiech et al., 2019a), and differentiated between the technical and conceptual uses of mathematics (Uhden et al., 2012, referring to Pietrocola, 2008). In contrast, our study focuses on the perspectives of STEM teachers in higher education, employing a phenomenographic approach to deeply understand variations among their conceptions. This can inform future work specifically exploring how these views influence their teaching and students' learning opportunities.

Redish (2015) notes that while mathematics is integral to teaching and practising physics, other sciences, such as chemistry, biology, geology, and meteorology, often use it extensively but less so in educational settings. Our study involved teachers from chemistry, computer science, geoscience, and physics, revealing similar mathematical conceptions across these disciplines. Nevertheless, we do not aim to discuss differences between the disciplines. We focused on the whole group of STEM teachers, which is in line with our research question and the phenomenographic approach. It would also not be appropriate to compare the disciplines due to the large discrepancies in the number of interviews per discipline and the total number of interviews being relatively small. The similarities observed, particularly in the first three categories, align with previous student studies and studies on school teachers (e.g., Pospiech et al., 2019a), supporting our arguments that these findings are relevant and useful.

The first category fits well with previous studies on students' views on mathematics, which categorises mathematics as a tool for numerical calculations. While crucial for STEM fields, as emphasized by for example Lutz and Srogi (2000), it can hinder learning. Uhden et al. (2012) argued that regarding mathematics solely as a calculation tool in physics limits conceptual understanding. They advocated for a deeper exploration of the relationship between mathematics and physics in both teaching and research.

The second category extends the notion of mathematics as a tool by using it to describe the discipline more precisely and efficiently. This is in line with Fitzallen (2015), viewing mathematics as fundamental to STEM fields, serving as their language. Students who have not discerned this aspect omit central parts of the discipline, such as using mathematics for modelling and expanding knowledge structures. Modelling is an integral part of STEM disciplines, and Bain et al. (2019) argue that mathematical fluency is required to be able to take part in science. Additionally, Baldwin et al. (2013) argue that articulating reasoning in mathematical terms can enhance understanding, citing its relevance in computer science.

The third category describes the conception of mathematics as a way to understand the discipline, which is related to the second category, and perhaps the very reason mathematics is used as a language for other STEM disciplines. This category contributes to the complexity of the role of mathematics in the disciplines, which has been relatively underexplored in literature (Fitzallen, 2015). Kristensen et al. (2024) presented practical perspectives in their review of the role of mathematics in STEM teaching activities, where one of the roles involved mathematics as a support for a deeper understanding of the science or technology. Also, de Ataíde and Greca (2013) argue that mastering problem solving requires integrating mathematical and physical concepts. Similarly, Beaubouef (2002) discusses how proficiency in mathematics facilitates abstraction, needed for advanced problem solving in computer science.

The fourth category, viewing mathematics as an agent for development, builds upon the previous categories and diverges from perceptions found amongst physics students (de Ataíde & Greca, 2013). It also aligns with the notion of deep engagement with subject-specific mathematics (Baldwin et al., 2013). In order to discern the process of research, and by that what it means to do science, the role of the scientific method, and the connection between a scientific theory and a reality in terms of controlled experiments, it can be argued that it is important that the conception of category 4 is embraced by students. Uhden et al. (2012) highlight the profound link between physics and mathematics, suggesting that mathematics drives the evolution of physics and scientific models, a sentiment echoed by participants in the study.

The fifth category, a philosophical foundation, adds a perspective on the deep and intertwined relationship between mathematics and the discipline. This last category ends up in the domain of the philosophy of science by speculating about the nature of mathematics. As pointed out by one interviewee, if this philosophical position is taken too far, it can be problematic since it can lead to deviation from the principles of natural sciences. We want to emphasise that this category provides an important point of view to consider, since it could deeply affect the way in which research and teaching activities are carried out.

The emergence of philosophical conceptions among our participants – particularly critiques of Platonist thinking – aligns with longstanding debates in the philosophy of mathematics. Platonism posits that mathematical objects and truths exist independently of human minds, waiting to be discovered, while formalist perspectives view mathematics as a human-constructed system of rules and symbols (Ernest, 1985). The reflections shared by some participants, especially those questioning the "independent existence of mathematics" resonate strongly with non-Platonist positions. Similar distinctions have also been discussed in the context of computer science, where Eden (2007) identifies competing paradigms that reflect different ontological and epistemological views on the nature of computing and mathematics. In addition, Spindler (2022) highlights how foundational beliefs about mathematics – such as Platonism and Formalism – may carry ethical implications in education, shaping how mathematical knowledge is taught and perceived. Although our study does not aim to resolve these philosophical questions, the presence of such discourse among STEM educators suggests that these foundational views may influence not only research but also teaching practices and students' understanding of mathematics. Future research might explore more systematically how philosophical positions about mathematics are held, communicated, or acted upon in STEM education.

In contrasting our findings with the broader recent discourses of the role of mathematics in STEM education (e.g., Maass et al., 2019; Forde et al., 2023), a notable distinction emerges. Commonly, studies tend to merge the nuanced roles of mathematics into less differentiated conceptions. This is particularly evident in the blending of categories similar to our third and fourth. These are often grouped into one conception that simultaneously acknowledges mathematics' significance in improving understanding of the discipline and facilitating disciplinary advancement. One exception was recently proposed by Palmgren and Rasa (2024), who characterised the role of mathematics in physics into four parts, similar to our categories 1–4. We concur with their emphasis on distinguishing these roles, and the importance of including theory structure and generation of new knowledge in the discourse.

Furthermore, our investigation enriches the discourse by presenting a fifth category of conceptions, with a dimension less directly addressed in existing studies with similar contexts. While foundational aspects of mathematics are widely recognised, they are often described in a generic manner, highlighting mathematics as a core

underpinning of other STEM disciplines without delving into its philosophical implications (e.g., Kristensen et al., 2024). It is interesting that the philosophical discussion emerged from the teachers, particularly with respect to debates about Platonism, as one might expect such discussions to be distant from teaching practices. While these themes are prevalent in the established literature on the philosophy of mathematics, as mentioned previously, our work indicates the relevance of further investigating how such philosophical positions can influence teaching approaches, and consequently learning, in STEM disciplines.

The ability to identify the subtle differences between these categories highlights the strength of the phenomenographic approach used in our research. Through in-depth interviews with university teachers across various STEM disciplines, we were able to capture a rich spectrum of conceptions. This methodological choice facilitated the emergence of insights that might remain hidden in studies employing more deductive approaches or focusing solely on technical or structural frameworks.

Implications for teaching

Considering possible implications for teaching, the fact that our categories transcend disciplines in STEM suggests that our students should meet a common culture in the classroom. However, even though teachers may personally subscribe to such a diversity of conceptions, they may not make this explicit to students in their own teaching. This echoes the discussion in similar work on school teachers (e.g., Pospiech et al., 2019a). Many students, including those in advanced stages, often have a narrow understanding of mathematics' role, with the broader views uncommon among students, as shown by de Ataíde and Greca (2013). Their results were in line with our first three categories, and although the students were in their last year, they often were limited to the first category. This is troublesome, especially because de Ataíde and Greca (2013) noticed a close relationship between the students' epistemic view on the role of mathematics in physics and their problem-solving abilities.

Previous research shows that students rarely discuss the more advanced roles of mathematics, which include its contribution to understanding, development, and philosophical foundation of the other STEM disciplines. We suggest that expanding students' view of mathematics beyond simple computation to these broader roles could enhance STEM education and increase interest in STEM research. We find it important that teachers are aware of most of the categories, and that it is meaningful to communicate the role of mathematics to the students, as echoed by some of our participants.

Teachers' conceptions of the role of mathematics can influence their teaching approaches, which in turn affects students' conceptions and success in the discipline. Notably, recent work (Kristensen et al., 2024) suggests that the role of mathematics in published STEM teaching activities mainly correspond to the characteristics of our first and third category, or that the purpose of the activity is to master the mathematics itself. Recognising the diversity of these conceptions can help teachers become more aware of their students' views and adjust their teaching strategies and design activities accordingly. Teachers in each discipline need to consider how to incorporate these aspects in their own contexts.

Although teachers might share similar views, they may not discuss the multifaceted roles of mathematics with colleagues, which could otherwise foster more developed understandings. We think that such discussions would be beneficial in the development of more sophisticated views, not least for less experienced university teachers than the participants in this study (cf. Table 1). Even when teachers have a refined view, this might not transfer to the students without meta-discussions on the various ways that mathematics is inherent in other disciplines. An example of the application of such meta-discussions would be in the development of "bridging" courses (cf. shadow courses, Lutz & Srogi, 2000), where mathematics would be taught in parallel with another STEM discipline, so that role of mathematics in the other STEM discipline could be clearly discerned and applied. We believe that the different roles need to be made explicit to students, to promote their learning of both mathematics and other STEM disciplines. We suggest that teachers should allocate specific time to address these aspects in their lesson planning and engage in collegial discussions to effectively integrate these concepts across disciplines.

Limitations

This study involved researchers from diverse fields interviewing experienced colleagues. The researchers' insights, and their own conceptions about the role of mathematics in their particular STEM discipline, could influence the interviews and the interpretation of data. Therefore, careful measures were taken to prevent bias in questioning and categorisation. The extensive interview protocol, including sub-questions, was thoroughly discussed by the researchers to avoid any leading questions or the introduction of own ideas. Furthermore, to minimise the influence of personal biases, the categorisation was conducted in stages: first by individuals, then in groups, and finally by the entire research team.

Although the collegial framing in this study may help participants feel more at ease – making the interview resemble an academic conversation – it also presents a potential limitation. Interviewing colleagues means that past and future interactions could influence what is said or omitted. Informants might refrain from mentioning

what they consider obvious and may avoid saying anything that could create a negative impression. To mitigate this potential issue, we asked the interviewees to elaborate their ideas and asked follow-up questions. Additionally, we encouraged them to discuss ideas they thought their colleagues might have, rather than their own views. Since the topic was the role of mathematics in other STEM disciplines, we believe that the interviewees might rather make an effort to give clever answers, than avoid expressing their thoughts. This would result in a richer outcome, not a limited one. Had the topic been more sensitive, the risk of being seen in an unfavourable light might have been more influential. These strategies helped to shift the focus from self-presentation to reflection, enabling participants to explore and articulate a range of views without feeling personally evaluated. Moreover, by asking about colleagues' perspectives and practices, we created distance from the interviewee's own stance, which allowed them to surface multiple conceptions – including ones they might not fully endorse themselves.

Variations in interviewing styles could affect findings, but also offer diverse perspectives. While interviewing across STEM disciplines may have limitations, consistent answers suggest holistic insights. The limited number of interviews and their uneven distribution between the disciplines does not allow for a more fine-grained analysis of differences between subjects.

While our participants were experienced academics with significant teaching experience which may limit access to some perspectives of early-career educators – this aligns with our aim to capture a broad range of conceptions, including both basic and more developed ones. In phenomenography, variation often best surfaced through participants who have deeply engaged with the phenomenon, and under its theoretical assumptions, even less developed conceptions can be captured through reflective accounts from experienced individuals. Future research could investigate if early-career teachers hold other conceptions of mathematics in their disciplines.

Conclusions and future work

This empirical study is one of the first to systematically investigate STEM university teachers' conceptions of mathematics in their discipline. In order to capture as much variation as possible, we adopted a phenomenographic approach and let the categories of conceptions emerge from the interview data. We identified five distinct and hierarchically inclusive categories of conceptions, distinguishing and revealing dimensions that are often overlooked in existing literature. Our work contributes to raising awareness among educators about the implicit conceptions they may hold and how these may shape their instructional approaches. The diversity of views highlighted here invites STEM educators to reflect on their own assumptions about mathematics, encouraging a deeper consideration of how their perspectives may influence students' engagement and comprehension. This shift in awareness can serve as a foundation for more deliberate and reflective teaching practices, which future research can build upon to translate these insights into practical pedagogical strategies. Future research could expand this work across a broader range of STEM disciplines and incorporate longitudinal studies to explore how changes in educators' awareness influence their teaching approaches over time and affect student learning outcomes. Further valuable insights could emerge from investigating the connections between teachers' conceptions of what mathematics is and our findings about their view of the roles it plays in their STEM discipline. This study does not aim to discern differences in conceptions of mathematics between disciplines. That would, however, be an interesting direction to pursue in further studies where more data from the different disciplines would be collected.

Acknowledgements
We acknowledge the support of the Uppsala University Centre for Discipline-Based Education Research in STEM disciplines (MINT). We also thank all the teacher volunteers who participated in this study.

Author contributions
AE, ME and FMH initiated and designed the study, and the overall project was led by AE. All authors contributed to the preparation of materials, and the data collection was performed by all authors except AE. The findings are based on an initial analysis by EK, GP, LF and AS, which was further developed together with AE, FMH, ME, RBH and LE. All authors were involved in writing the first draft of the manuscript and providing comments. All authors read and approved the final manuscript. EK and GP contributed equally as first authors.

Funding
No funding to declare.

Data availability
The semi-structured interview protocol is available in the supplementary material. Anonymised transcribed data are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent
The participants provided informed consent and the study was conducted in accordance with the General Data Protection Regulation [(GDPR) (EU) 2016/679]. Ethical approval from the Swedish Ethical Review Authority was not required since sensitive personal data were not collected.

Competing interests
The authors declare no competing interests.

Received: 4 December 2024 / Accepted: 28 June 2025
Published online: 07 July 2025

References

Åkerlind, G. S. (2018). What future for phenomenographic research? On continuity and development in the phenomenography and variation theory research tradition. *Scandinavian Journal of Educational Research*, *62*(6), 949–958.

Bain, K., Rodriguez, J-M-G., & Towns, M. H. (2019). Chemistry and mathematics: Research and frameworks to explore student reasoning. *Journal of Chemical Education*, *96*, 2086–2096. https://doi.org/10.1021/acs.jchemed.9b00523

Baldwin, D., Walker, H. M., & Henderson, P. B. (2013). The roles of mathematics in computer science. *Acm Inroads*, *4*(4), 74–80. https://doi.org/10.1145/2537753.2537777

Beaubouef, T. (2002). Why computer science students need math. *ACM SIGCSE Bulletin*, *34*(4), 57–59. https://doi.org/10.1145/820127.820166

Berglund, A., Eckerdal, A., Pears, A., East, P., Kinnunen, P., Malmi, L.,... Thomas, L. (2009). Learning computer science: Perceptions, actions and roles. *European Journal of Engineering Education*, *34*(4), 327–338. https://doi.org/10.1080/03043790902989168

Blum, W., & Leiss, D. (2005). "Filling Up"-the problem of independence-preserving teacher interventions in lessons with demanding modelling tasks. In *CERME 4–Proceedings of the Fourth Congress of the European Society for Research in Mathematics Education (Vol. 1623)*. Sant Feliu de Guíxols: FUNDEMI IQS–Universitat.

Booth, S. (2008). Symposium 9: Researching Learning in Networked Learning–Phenomenography and Variation theory as empirical and theoretical approaches. In Proceedings of the International Conference on Networked Learning (6), 450–455.

Branchetti, L., Cattabriga, A., & Levrini, O. (2019). Interplay between mathematics and physics to catch the nature of a scientific breakthrough: The case of the blackbody. *Phys Rev Phys Educ Res*, *15*, 02013. https://doi.org/10.1103/PhysRevPhysEducRes.15.020130

Carminati, L. (2018). Generalizability in qualitative research: A Tale of two traditions. *Qualitative Health Research*, *28*(13), 2094–2101.

de Almeida, M. B., Gomes, A., Margalho, L., Branco, J. R., & Fidalgo, C. (2023). Failure rates in Maths and CS 1: are they associated? In *2023 IEEE Global Engineering Education Conference (EDUCON)* (pp. 1–6). IEEE.

de Ataíde, A. R. P., & Greca, I. M. (2013). Epistemic views of the relationship between physics and mathematics: Its influence on the approach of undergraduate students to problem solving. *Science & Education*, *22*, 1405–1421. https://doi.org/10.1007/s11191-012-9492-2

Doig, B., Williams, J., Swanson, D., Ferri, R. B., & Drake, P. (2019). Interdisciplinary mathematics education: The state of the art and beyond. https://doi.org/10.1007/978-3-030-11066-6

Dreyfus, T., González-Martín, A. S., Nardi, E., Monaghan, J., E., & Thompson, P. W. (2023). The Learning and Teaching of Calculus Across Disciplines – Proceedings of the Second Calculus Conference MatRIC. https://matriccalcconf2.sciencesconf.org/.

Eckerdal, A., Berglund, A., & Thuné, M. (2024). Learning programming practice and programming theory in the computer laboratory. *European Journal of Engineering Education*, *49*(2), 330–347. https://doi.org/10.1080/03043797.2023.2294953

Eden, A. H. (2007). Three paradigms of computer science. *Minds and Machines*, *17*, 135–167. https://doi.org/10.1007/s11023-007-9060-8

Ernest, P. (1985). The philosophy of mathematics and mathematics education. *International Journal of Mathematical Education in Science and Technology*, *16*(5), 603–612. https://doi.org/10.1080/0020739850160505

Fitzallen, N. (2015). STEM education: What does mathematics have to offer? In M. Marshman, V. Geiger, & A. Bennison (Eds.). *Mathematics education in the margins* (Proceedings of the 38th annual conference of the Mathematics Education Research Group of Australasia), pp. 237–244. Sunshine Coast: MERGA

Forde, E. N., Robinson, L., Ellis, J. A., & Dare, E. A. (2023). Investigating the presence of mathematics and the levels of cognitively demanding mathematical tasks in integrated STEM units. *Disciplinary and Interdisciplinary Science Education Research*, *5*(1), 3. https://doi.org/10.1186/s43031-022-00070-1

Gibbons, R. E., Villafañe, S. M., Stains, M., Murphy, K. L., & Raker, J. R. (2018). Beliefs about learning and enacted instructional practices: An investigation in postsecondary chemistry education. *J Res Sci Teach*, *55*, 1111–1133. https://doi.org/10.1002/tea.21444

Goos, M., Carreira, S., & Namukasa, I. K. (2023). Mathematics and interdisciplinary STEM education: Recent developments and future directions. *ZDM– Mathematics Education*, *55*, 1199–1217.

Greca, I. M., & de Ataíde, A. R. P. (2019). Theorems-in-action for problem-solving and epistemic views on the relationship between physics and mathematics among preservice physics teachers. In G. Pospiech, M. Michelini, & B. S. Eylon (Eds.), *Mathematics in physics education* (pp. 153–173). Springer. https://doi.org/10.1007/978-3-030-04627-9_7

Henderson, P. B. (2005). The role of mathematics in computer science and software engineering education. *Advances in Computers*, *65*, 349–395. https://doi.org/10.1016/S0065-2458(05)65008-5

Hofer, B. K. (2001). Personal epistemology research: Implications for learning and teaching. *Educational Psychology Review*, *13*, 353–383. https://doi.org/10.1023/A:1011965830686

Ho, F. M., Elmgren, M., Rodriguez, J. M. G., Bain, K. R., & Towns, M. H. (2019). Graphs: Working with models at the crossroad between chemistry and mathematics. *It's just math: Research on students' Understanding of chemistry and mathematics* (pp. 47–67). American Chemical Society.

Ingerman, Å., & Booth, S. (2003). Expounding on physics: A phenomenographic study of physicists talking of their physics. *Int J Sci Educ*, *25*(12), 1489–1508. https://doi.org/10.1080/0950069032000070298

Karam, R., Uhden, O., & Höttecke, D. (2019). The math as prerequisite illusion: Historical considerations and implications for physics teaching. In G. Pospiech, M. Michelini, & B. S. Eylon (Eds.), *Mathematics in physics education* (pp. 37–52). Springer. https://doi.org/10.1007/978-3-030-04627-9_2

Knuth, D. E. (1974). Computer science and its relation to mathematics. *The American Mathematical Monthly*, *81*(4), 323–343. https://doi.org/10.2307/2318994

Koballa, T., Graber, W., Coleman, D. C., & Kemp, A. C. (2000). Prospective gymnasium teachers' conceptions of chemistry learning and teaching. *International Journal of Science Education*, *22*(2), 209–224. https://doi.org/10.1080/095006900289967

Krey, O. (2019). What Is Learned About the Roles of Mathematics in Physics While Learning Physics Concepts? A Mathematics Sensitive Look at Physics Teaching and Learning. In: Pospiech, G., Michelini, M., Eylon, BS. (Eds.) *Mathematics in Physics Education*. Springer, Cham., 102–123. https://doi.org/10.1007/978-3-030-04627-9_5

Kristensen, M. L. A., Larsen, D. M., Seidelin, L., & Svabo, C. (2024). The role of mathematics in STEM activities: Syntheses and a framework from a literature review. *International Journal of Education in Mathematics Science and Technology*, *12*(2), 418–431. https://doi.org/10.46328/ijemst.3357

Kussuda, S. R., & Nardi, R. (2019). Some reasons that influence dropout in a Physics Teachers Training program. In *Journal of Physics: Conference Series*, *1286*(1), 012042. IOP Publishing. https://doi.org/10.1088/1742-6596/1286/1/012042

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic inquiry*. Sage.

Lutz, T. M., & Srogi, L. (2000). The role of a shadow course in improving the mathematics skills of geoscience majors. *Journal of Geoscience Education*, *48*(4), 474–478. https://doi.org/10.5408/1089-9995-48.4.474

Maass, K., Geiger, V., Ariza, M. R., & Goos, M. (2019). The role of mathematics in interdisciplinary STEM education. *Zdm*, *51*, 869–884. https://doi.org/10.1007/s11858-019-01100-5

Macdonald, R. H., & Bailey, C. M. (2000). Integrating the teaching of quantitative skills across the geology curriculum in a department. *Journal of Geoscience Education*, *48*(4), 482–486. https://doi.org/10.5408/1089-9995-48.4.482

Manduca, C. A., Baer, E., Hancock, G., Macdonald, R. H., Patterson, S., Savina, M., & Wenner, J. (2008). Making undergraduate geoscience quantitative. *Eos Transactions American Geophysical Union*, *89*(16), 149–150. https://doi.org/10.1029/2008EO160001

Marshall, D., & Linder, C. (2005). Students' expectations of teaching in undergraduate physics. *International Journal of Science Education*, *27*(10), 1255–1268. https://doi.org/10.1080/09500690500153691

Marton, F. (2014). *Necessary Conditions of Learning*: Routledge. ISBN: 9780415739146.

Marton, F., & Booth, S. (1997). *Learning and awareness*. L. Erlbaum Associates.

Marton, F., Tsui, A. B., Chik, P. P., Ko, P. Y., & Lo, M. L. (2004). *Classroom discourse and the space of learning*. Routledge. ISBN: 9780805840094.

Olafson, L., & Schraw, G. (2006). Teachers' beliefs and practices within and across domains. *International Journal of Educational Research*, *45*(1–2), 71–84. https://doi.org/10.1016/j.ijer.2006.08.005

Palmgren, E., & Rasa, T. (2024). Modelling roles of mathematics in physics. *Sci & Educ*, *33*, 365–382. https://doi.org/10.1007/s11191-022-00393-5

Paulson, H. G. (2002). Computer science students need adequate mathematical background. In *International conference on the teaching of mathematics* (*Vol. 2*).

Pietrocola, M. (2008). Mathematics as structural Language of physical thought. In M. Vicentini, & E. Sassi (Eds.), *Connecting research in physics education with teacher education* (Vol. *2*). International Commission on Physics Education.

Popova, M., Shi, L., Harshman, J., Kraft, A., & Stains, M. (2020). Untangling a complex relationship: Teaching beliefs and instructional practices of assistant chemistry faculty at research-intensive institutions. *Chemical Education Research and Practice*, *21*, 513–527. https://doi.org/10.1039/c9rp00217k

Pospiech, G., Eylon, B. S., Bagno, E., & Lehavi, Y. (2019a). Role of teachers as facilitators of the interplay physics and mathematics. In G. Pospiech, M. Michelini, & B. S. Eylon (Eds.), *Mathematics in physics education* (pp. 269–292). Springer. https://doi.org/10.1007/978-3-030-04627-9_12

Pospiech, G., Lehavi, Y., Bagno, E., & Eylon, B. S. (2019b). Views and strategies of teachers concerning the role of mathematics and physics in physics lessons. In E. McLoughlin, & van P. Kampen (Eds.), *Concepts, strategies and models to enhance physics teaching and learning* (pp. 181–192). Springer. https://doi.org/10.1007/978-3-030-18137-6_16

Prosser, M., Trigwell, K., & Taylor, P. (1994). A phenomenographic study of academics' conceptions of science learning and teaching. *Learning and Instruction*, *4*(3), 217–231. https://doi.org/10.1016/0959-4752(94)90024-8

Quale, A. (2011). On the role of mathematics in physics. *Sci & Educ*, *20*, 359–372. https://doi.org/10.1007/s11191-010-9278-3

Redfors, A., Hansson, L., Hansson, Ö., & Juter, K. (2016). A framework to explore the role of mathematics during physics lessons in Upper-Secondary school. In N. Papadouris, A. Hadjigeorgiou, & C. Constantinou (Eds.), *Insights from research in science teaching and learning. Contributions from science education research* (Vol. 2, pp. 139–151). Springer.

Redish, E. F., & Gupta, A. (2009). Making meaning with math in physics: A semantic analysis. *GIREP-EPEC & PHEC 2009*, 244.

Redish, E. F., & Kuo, E. (2015). Language of physics, Language of math: Disciplinary culture and dynamic epistemology. *Sci & Educ*, *24*, 561–590. https://doi.org/10.1007/s11191-015-9749-7

Spindler, R. (2022). Foundational mathematical beliefs and ethics in mathematical practice and education. *Journal of Humanistic Mathematics*, *12*(2), 49–71. https://doi.org/10.5642/jhummath.GOSN2205

Steiner, M. (2009). *The applicability of mathematics as a philosophical problem*. Harvard University Press.

Stillman, G. A., Ikeda, T., Schukajlow, S., de Loiola Araújo, J., & Ärlebäck, J. B. (2024). Interdisciplinary Aspects of the Teaching and Learning of Mathematical Modelling in Mathematics Education Including Relations to the Real World and STEM. In Wang, J., (Ed.) *Proceedings of the 14th International Congress on Mathematical Education*, https://doi.org/10.1142/9789811287152_0024

Towns, M. H., Bain, K., & Rodriguez, J. M. G. (2019). How did we get here? Using and applying mathematics in chemistry. *It's just math: Research on students' Understanding of chemistry and mathematics* (pp. 1–8). American Chemical Society.

Trigwell, K. (2006). Phenomenography: An approach to research into geography education. *Journal of Geography in Higher Education*, *30*(2), 367–372. https://doi.org/10.1080/03098260600717489

Tuminaro, J., & Redish, E. F. (2007). Elements of a cognitive model of physics problem solving: Epistemic games. *Phys. Rev. ST Phys. Educ. Res.*, 3(2), 020101. https://doi.org/10.1103/PhysRevSTPER.3.020101

Tzanakis, C., & Thomaidis, Y. (2000). Integrating the Close Historial Development of Mathematics and Physics in Mathematics Education: Some Methodological and Epistemological Remarks, For the Learning of Mathematics, FLM Publishing Association, pp 44– 55.

Uhden, O., Karam, R., Pietrocola, M., & Pospiech, G. (2012). Modelling mathematical reasoning in physics education. *Science & Education*, *21*, 485–506. https://doi.org/10.1007/s11191-011-9396-6

Wenner, J. M., Baer, E. M., Manduca, C. A., Macdonald, R. H., Patterson, S., & Savina, M. (2009). The case for infusing quantitative literacy into introductory geoscience courses. *Numeracy*, *2*(1), Article 4. https://doi.org/10.5038/1936-4660.2.1.4

Wilson, B. C., & Shrock, S. (2001). Contributing to success in an introductory computer science course: A study of twelve factors. *ACM SIGCSE Bulletin*, *33*(1), 184–188. https://doi.org/10.1145/366413.364581

Ye, S., Elmgren, M., Jacobsson, M., & Ho, F. M. (2024). How much is just maths? Investigating problem solving in chemical kinetics at the interface of chemistry and mathematics through the development of an extended mathematical modelling cycle. *Chemical Education Research and Practice*, *25*, 242–265. https://doi.org/10.1039/D3RP00168G

Ye, S., Jacobsson, M., Elmgren, M., & Ho, F. M. (2025). 'It just feels like it's gonna be so very long?' Exploring the resources used by university students in noticing, navigating, and resolving issues during math-intensive problem solving in chemistry. *Chemical Education Research and Practice*, *26*, 377–397. https://doi.org/10.1039/D4RP00227J

Publisher's note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.