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# Analyzing graph usage in chemistry textbooks and its implications for learning and teaching

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Graphs play a central role in chemistry education, serving as powerful tools for visualizing abstract concepts. However, their high information density and abstract nature can overwhelm students, often resulting in learning difficulties. Developing graph competence is therefore essential. While research on graph use and comprehension is well established in science education, investigations specific to chemistry remain limited. This study addresses this gap by systematically analyzing the use of graphs in eight German middle and secondary school chemistry textbooks, identifying and examining 3550 visual representations to provide a more precise understanding of graph use in chemistry and its implications for learning and teaching. The analysis quantified and compared the prevalence and distribution of graphs and realistic pictures across content areas and educational levels. Focusing on line graphs, we also analyzed how graph-related textbook tasks engage students in cognitive processes at varying levels of complexity. Our findings reveal not only the variety of graph types in chemistry textbooks but also distinct differences in the cognitive demands placed on students across educational levels and school types. Furthermore, they highlight domain-specific characteristics of graphs in chemistry and suggest challenges that students are likely to encounter when engaging with them. By identifying these patterns, the study extends previous research on graph use through its focused chemistry education context and provides actionable insights for improving textbook design and instructional strategies. Finally, this work lays the groundwork for future research into students' actual graph competence and graph-related difficulties.



## Introduction

"A picture is worth a thousand words" – this well-known saying underscores the powerful role of visual representations in communicating complex information. In chemistry education, visual representations such as graphs and realistic pictures are essential tools for fostering understanding, supporting reasoning, and enabling problem-solving. Graphs are distinct in that they depict relationships between variables, typically with at least one being continuous. Scales define the possible range of values a variable can take, allowing for precise description and interpretation based on position along the axes (Schnotz, 2001). Successfully engaging with graphs requires graph competence, the cognitive ability to extract information from graphs and to construct them meaningfully (Lachmayer, 2008). The critical role of graphs and the need for graph competence span societal, scientific, and educational domains.

As Pozzer and Roth (2003, p. 1108) observe, we live in a "visual culture," making the ability to interpret and critically evaluate graphical data increasingly essential from a societal perspective. Graphs dominate public discourse, from environmental trends to market statistics, and their misinterpretation can easily fuel misinformation (Berg and Smith, 1994). Today, in light of growing concerns about misinformation and the complexity of modern media, the ability to competently engage with data has become a key skill for everyday life in both analog and digital contexts. Ögren *et al.* (2017, p. 282) illustrate this pointedly, showing that "when seeing a graph, students are more likely to believe in the correctness of the accompanying statements" – regardless of whether the statements are true or false. Graph competence thus contributes to statistical literacy, enabling individuals to understand and critically evaluate statistical representations (Gal, 2002; Aoyama and Stephens, 2003; Aoyama, 2006).

From a scientific perspective, graphs are indispensable tools in the natural sciences, where competence in graph use is fundamental to scientific practice (Berg and Smith, 1994; Bowen and Roth, 1998; Roth *et al.*, 1999; Bowen and Roth, 2005; Arneson and Offerdahl, 2018). Graphs serve multiple functions: summarizing large datasets (Bowen and Roth, 2005), supporting the interpretation of scientific publications (Bowen and Roth, 1998), and functioning as cognitive tools for

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reasoning (Von Kotzebue *et al.*, 2015), meaning making (Kozma and Russell, 2005), and explanation (Bowen and Roth, 1998). While graphs are vital across disciplines, their use and conventions are often context- and domain-specific (Ainsworth, 2006; Talanquer, 2022), reflecting the types of information most relevant to each field (Bowen and Roth, 1998; Ring and Brahm, 2020; Brockmüller and Ropohl, 2025). For instance, Shanahan *et al.* (2011) demonstrate that disciplinary experts engage differently with visual representations – chemists, for example, tend to regard textual and visual representations as equally valid sources of information. This underscores why chemistry is often described as a "visual science" (Wu and Shah, 2004, p. 465; Han and Roth, 2006, p. 199; Upahi and Ramnarain, 2019, p. 154), highlighting the particular importance of visual representations in this field. However, focusing exclusively on domain-specific characteristics risks overlooking broader principles of visual representations. Thus, understanding both the general principles and discipline-specific nuances of visual representations, particularly graphs, promotes a more comprehensive perspective. Therefore, while this article focuses on the use of graphs in chemistry, its insights extend across the sciences and contribute to advancing science education more broadly.

From an educational perspective, it is important to distinguish between graphs used in scientific research and those used for educational purposes. While research graphs tend to be more complex and abstract (Roth *et al.*, 1999), in both contexts they serve to visualize data and explain phenomena. Thus, early exposure to graphs is essential for developing scientific literacy (*e.g.*, Padilla *et al.*, 1986) and scientific inquiry skills (*e.g.*, Von Kotzebue *et al.*, 2015), aligning classroom practices with authentic scientific reasoning (Krohn, 1991).

Despite their ubiquity, graphs have an ambiguous role in educational contexts. Generally, students encounter graphs frequently throughout their science education (Bowen and Roth, 2002; Ring and Brahm, 2020). Under the right conditions, graphs support learning by helping students visualize data (Bowen and Roth, 2002; Boels *et al.*, 2019), develop methodological skills (Ring and Brahm, 2020), enhance reasoning and transfer abilities (Stern *et al.*, 2003), support communication (Boels *et al.*, 2019; Ring and Brahm, 2020), and foster critical thinking (Ring and Brahm, 2020). Accurate reading and interpretation of graphs are thus essential for acquiring subject-specific knowledge. The importance of graph competence is also reflected in international curricula, such as those of North Rhine-Westphalia, Germany (*e.g.*, Ministerium für Schule und Weiterbildung des Landes Nordrhein-Westfalen, 2022), the U.S. Next Generation Science Standards (National Research Council, 2013), and the U.K. National Curriculum for Science (Department for Education, 2013).

However, graphs also pose challenges. Understanding them is not intuitive for students (*e.g.*, Dreyfus and Eisenberg, 1990; Ring and Oberrauch, 2024), and research documents numerous difficulties in learning and interpreting graphs due to their complexity and abstract nature (*e.g.*, Padilla *et al.*, 1986; McDermott *et al.*, 1987; Leinhardt *et al.*, 1990; Bowen and Roth, 2002; Glazer, 2011; Jahnke, 2020; Ring and Brahm, 2020; Brockmüller and Ropohl, 2025). A comparison of scientific and educational perspectives reveals a paradox: what is advantageous in science – the abstract and compact representation of complex data – can become a barrier in educational settings. In chemistry education, two levels of abstraction therefore converge: the abstract nature of the scientific content and the abstract form of the graphical representation, creating a dual abstraction. To adequately address the difficulties students face when working with graphs, it is essential to strengthen graph competence, particularly in chemistry education (Glazer, 2011; Lai *et al.*, 2016).

### Research landscape and research gap

Research on graph use and graph competence spans various disciplines, including science education (*e.g.*, Isberner *et al.*, 2013), mathematics (*e.g.*, Curcio, 1987; Leinhardt *et al.*, 1990; Ainley, 2000; Ögren *et al.*, 2017), geography (*e.g.*, Mautone and Mayer, 2007; Brahm *et al.*, 2023), physics (*e.g.*, McDermott *et al.*, 1987; Nixon *et al.*, 2016), economics (*e.g.*, Stern *et al.*, 2003; Hey, 2005; Ring and Brahm, 2020), and biology (*e.g.*, Bowen and Roth, 1998; Roth *et al.*, 1999; Lachmayer, 2008; Von Kotzebue *et al.*, 2015; Jahnke, 2020). Although research in science education has documented general difficulties students face when engaging with graphs (*e.g.*, Glazer, 2011), comparatively little is known about how graphs are used and function in chemistry education specifically. This is noteworthy because graphs are highly context dependent across scientific domains (see above), reflecting differences in symbolic conventions, data types, and representational purposes. Yet this field is growing: recent studies, for example, explore the integration of large language models as graphing tools (Subasinghe *et al.*, 2025) and the development of diagnostic instruments for assessing graph competence (Hamerská *et al.*, 2025). Against this backdrop, the present study provides a systematic analysis of school-level chemistry textbooks, offering a timely snapshot of graph use in chemical teaching and learning contexts. It also contributes to the expanding international research on visual representations in science education textbooks, which has focused primarily on textbooks from the United States (*e.g.*, Bowen and Roth, 2002; Lee, 2010; Rybarczyk, 2011), Greece (*e.g.*, Papageorgiou *et al.*, 2019), Canada (*e.g.*, Bowen and Roth, 2002), Brazil (*e.g.*, Pozzer and Roth, 2003), Korea (*e.g.*, Han and Roth, 2006), Portugal (*e.g.*, Carvalho *et al.*, 2007), Australia (*e.g.*, Liu and Treagust, 2013; Tang, 2023a, 2023b), and Turkey and India (*e.g.*, Aydin *et al.*, 2014). The present study broadens this perspective by providing insights from German chemistry textbooks. In doing so, it adds both a subject-specific and a regional dimension to the international discourse, responding to calls for more cross-national research in this field (Han and Roth, 2006).

### Aim and research question

The overarching aim of this research project is to address the identified research gap by investigating students' graph competence in chemistry and exploring ways to enhance it through targeted differentiation strategies. These strategies aim to inform teaching practice, guide the design of instructional material, and contribute to curriculum development.

The research is structured into three interrelated studies. To investigate students' graph competence and develop effective differentiation strategies, it is first necessary to establish a fundamental understanding of how graphs are used in chemistry. The present study responds to this need through a review of relevant literature and a systematic analysis of chemistry textbooks, providing practical insights into graph use in chemistry classrooms. The following research question guided the textbook analysis: *How are graphs used in chemistry textbooks?* This overarching question is further specified into four sub-questions (SQs):

SQ1: *How frequently are graphs used compared to realistic pictures?*
SQ2: *What types of graphs are used?*
SQ3: *In which content areas are graphs most frequently used?*
SQ4: *To which competence components and competence levels do graph-related tasks (line graphs) correspond?*

This article presents key findings from the textbook analysis and integrates them with existing literature on graph use in science and chemistry education, informing recommendations for targeted instructional design and student support. Given the exploratory nature of the research question and the open methodological design, the analysis also yielded supplementary findings beyond the initial sub-questions, offering additional perspectives for chemistry education and future research.

# Theoretical background

To provide meaningful insights into the use of graphs in chemistry textbooks and its implications for graph competence, the following section forms the theoretical foundation of this study. It begins by defining visual representations and distinguishing graphs from other forms, such as realistic pictures, to clarify the key terminology used throughout. Building on this, the two components of graph competence – information extraction and graph construction – are introduced, followed by an outline of the cognitive demands associated with information extraction tasks, which can be ordered along a continuum of increasing complexity. Finally, it discusses research on the role of textbooks in science classrooms.

### Visual representations

Graphs are a specific type of visual representation (*e.g.*, Pauwels, 2006; Höffler *et al.*, 2013; Liu and Treagust, 2013; LaDue *et al.*, 2015; Rau, 2017; Arneson and Offerdahl, 2018; Papageorgiou *et al.*, 2019; Talanquer, 2022; Tang, 2023a; Silva and Sasseron, 2025). The term is used variably in research, with alternative terms such as ''inscription'' (*e.g.*, Bowen and Roth, 2002; Han and Roth, 2006; Aydin *et al.*, 2014), ''visualization'' (*e.g.*, Kozma and Russell, 2005), ''graphical representation'' (*e.g.*, Ring and Brahm, 2020) and, from a linguistic perspective, ''non-textual explanation'' (Meyer and Pietzner, 2022). In this article, ''visual representation'' is used.

Visual representations – including graphs – are essential in science for supporting scientific thinking, communication, and meaning-making (Han and Roth, 2006; Raker and Holme, 2013; Tang, 2023a) and are integral to research practices (Bowen and Roth, 2002; see ''Introduction''). Scientific visual representations ''may refer to objects that are believed to have some kind of material or physical existence, but equally may refer to purely mental, conceptual, abstract constructs and/or immaterial entities'' (Pauwels, 2006, p. 2). These may include directly observable phenomena, such as the color change of a solution during a titration or the formation of a precipitate, as well as entities visible only through specialized techniques or instruments, such as molecular structures inferred from spectroscopic data or the energy profile of a chemical reaction (Pauwels, 2006; Silva and Sasseron, 2025).

In chemistry, where many structures and processes cannot be directly observed, visual representations are key to comprehension. Experts interpret and integrate multiple representations by constructing large, meaningful clusters grounded in underlying principles, whereas novices often form superficial links and struggle to establish meaningful connections across them (Schnotz, 2001; Kozma, 2003). As individuals are socialized into a scientific community, they adopt its representational systems to build and communicate understanding (Kozma and Russell, 2005). The relevance and frequency of specific visual representations vary across domains; for example, chromatograms are particularly characteristic of chemistry (Cook, 2011). Visual representations play a central role in scientific artifacts such as textbooks and scientific journal articles (Roth *et al.*, 1999; Bowen and Roth, 2002; Rybarczyk, 2011). Roth *et al.* (1999) found an average of 1.4 visual representations per page in high school biology textbooks and scientific journals, while Raker and Holme (2013) reported that over 90% of ACS organic chemistry exam items since 1982 have included at least one visual representation.

From an educational perspective, visual representations support learning (Upahi and Ramnarain, 2019; for diagrams specifically, see Chittleborough and Treagust, 2008) and engage distinct sense-making resources (Han and Roth, 2006). Different forms serve different purposes: photographs primarily attract attention (Pozzer-Ardenghi and Roth, 2005), whereas chemical diagrams explain, describe, instruct, and support the development of mental models (Chittleborough and Treagust, 2008). Graphs possess features that can both facilitate and impede learning (see above). These considerations underscore the need for effective strategies – especially in textbooks – to support students in comprehending and using different forms of visual representations. The following section therefore defines and distinguishes ''graph'' and ''realistic picture'' as a basis for subsequent analysis.

### Defining and distinguishing graphs and realistic pictures

Research offers various approaches and taxonomies for classifying visual representations (Ainsworth, 2006; LaDue *et al.*, 2015; Ring and Brahm, 2020; Tang, 2023a). In this study, we apply the classification developed by Schnotz (2001, 2002), which distinguishes visual representations based on the degree of similarity between the represented object and the representation itself (see also Schnotz and Bannert, 2003;

Lachmayer *et al.*, 2007). This framework differentiates between "descriptive" and "depictive" representations, each engaging distinct mental processes during reading and understanding. Descriptive representations (*e.g.*, texts or equations) use symbolic signs to denote relations. Their structure is arbitrary and governed by conventions (Schnotz, 2001, 2002; Schnotz and Bannert, 2003; Lachmayer *et al.*, 2007). In contrast, depictive representations (*e.g.*, realistic pictures and graphs) rely instead on structural features that correspond to structural aspects of the subject matter, with the correspondence serving as the representational function (Schnotz, 2001, 2002; Schnotz and Bannert, 2003). Depictive representations further divide into realistic and logical pictures (Schnotz, 2001; Lachmayer, 2008; Ring and Brahm, 2020). In realistic pictures, the relationship between the depicted object and its representation is directly visible, creating a concrete form of structural correspondence limited by the two-dimensional nature of the representation; in logical pictures such as graphs, correspondence is abstract, representing objects through analogical relationships rather than direct similarity (Schnotz, 2001). For instance, a line graph may represent non-spatial characteristics, such as birth rates, by using spatial distances.

Graphs differ from realistic pictures in that they illustrate relationships between variables, at least one of which is continuous. Scales define the range of possible values a variable can assume and allow variables to be interpreted based on their positions along the axes (Schnotz, 2001). Typically, the independent variable (*e.g.*, time, temperature) is on the horizontal axis, and the dependent variable (*e.g.*, concentration, solubility) on the vertical axis. The choice of graph type depends on the data: bar graphs are suited for categorical data or comparisons across discrete cases (*e.g.*, temperature when dissolving different salts), whereas line graphs represent relationships between continuous data (*e.g.*, temperature change over time during salt dissolution) (LaDue *et al.*, 2015; Brockmüller and Ropohl, 2025). Terminologically, the term "diagram" is sometimes used interchangeably with "graph" (*e.g.*, Dreyfus and Eisenberg, 1990; Von Kotzebue *et al.*, 2015). Another linguistic distinction is that the German word "Diagramm" generally corresponds to the English word "graph." In this study, "graph" is used as defined above. Realistic pictures can be further classified into iconic and schematic forms (Khine and Liu, 2017; Tang, 2023a), while graphs encompass line graphs, column charts, bar graphs, scatter plots, pie charts, scales, and special forms. Detailed operational definitions and examples are provided in Table 3 (see "Methodological approach"). With these classification criteria established, the following section introduces the concept of graph competence.

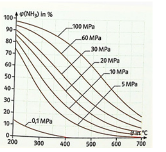
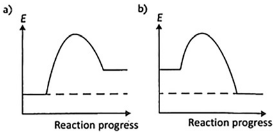
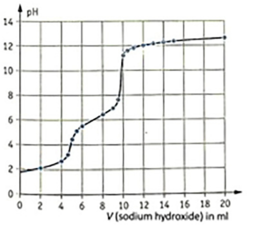
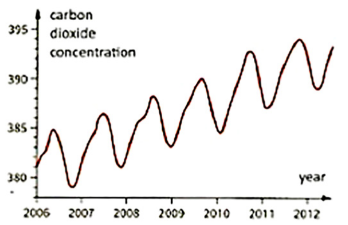
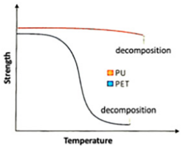
### Graph competence

The concept of "graph competence" (*e.g.*, Lachmayer, 2008; Ring and Oberrauch, 2024) is used with varying meanings in the research literature. Related terms include "graph comprehension" (Curcio, 1981, 1987; Carpenter and Shah, 1998; Friel *et al.*, 2001; Shah *et al.*, 2005; Mautone and Mayer, 2007; Lai *et al.*, 2016; Boels *et al.*, 2019), "graph literacy" (Galesic and Garcia-Retamero, 2011; Ring *et al.*, 2019), "graphic ability" (Berg and Smith, 1994), and "graphicacy" (Åberg-Bengtsson and Ottosson, 2006). Some studies use narrower terms, such as "graph interpretation" (Glazer, 2011; Peterman *et al.*, 2015) or "graphical reasoning" (Rodriguez *et al.*, 2019, 2020) to describe specific skills, whereas broader frameworks refer to "representational competence/competency" (Kozma and Russell, 2005; Rau, 2017; Wright *et al.*, 2018; Meyer and Pietzner, 2022; Talanquer, 2022; Graulich, 2025; Ward *et al.*, 2025), "inscription-related competencies" (Bowen and Roth, 2002), "graphical literacy" (Silva de Lima *et al.*, 2025), and "visual literacy" (Pauwels, 2006; Rybarczyk, 2011; Arneson and Offerdahl, 2018). These umbrella terms encompass the wider knowledge and skills needed to work with visual representations, including graphs (Kozma and Russell, 2005). Despite the terminological diversity, these concepts share overlapping meanings and refer to similar underlying abilities, a common structural distinction emerging across the literature: graph competence broadly encompasses two components – the extraction of information from a given graph, and the construction of a new graphs. Both components are relevant in chemistry education, where students are regularly expected to interpret graphs and to construct them, for example, in experimental contexts (*e.g.*, Brockmüller and Ropohl, 2025). The present textbook analysis addresses both components in the context of line graphs. Within the information extraction component, the cognitive demands placed on students vary considerably depending on the task. Therefore, these demands can be ordered along a continuum of increasing complexity, hereafter referred to as competence levels. This continuum includes five levels: level 1 – "Identification of a function value"; level 2 – "Description of graphs"; level 3 – "Interpretation of a function value"; level 4 – "Interpretation of one graph"; and level 5 – "Interpretation of more than one graph" (see Table 1).

As graph competence involves both domain-general and domain-specific knowledge (*e.g.*, Ring and Brahm, 2020), a distinction among the levels can be made. Levels 1 and 2 – such as describing a graph – are representation-specific, content-independent, and therefore transferable across disciplines. Conversely, the more cognitively demanding levels 3–5 are tightly bound to disciplinary contexts, requiring not only formal-representational but also domain-specific chemical knowledge, reflecting their subject-dependent nature.

Therefore, graph competence is domain-specific: research shows that scientists interpret graphs more accurately when they are familiar with the graph type (Roth and Bowen, 2001), and similar patterns have been observed among students (Bowen *et al.*, 1999; Åberg-Bengtsson and Ottosson, 2006). Moreover, prior experience with graphs strongly influences graph-related performance (Bowen *et al.*, 1999). Notably, successfully interpreting a line graph in mathematics does not ensure comprehension of the same graph type in chemistry, as graphical conventions and display practices often differ (Åberg-Bengtsson and Ottosson, 2006; Planinic *et al.*, 2012). Consequently, developing graph competence in chemistry requires fostering both general formal-representational graph

Table 1 Overview of the five competence levels with definitions and example tasks from textbooks. All textbook tasks and figures were taken from the original chemistry textbooks and translated into English by the authors, staying as close as possible to the original terminology

| Competence level | | Definition | Example task from textbook |
|---|---|---|---|
| Level 1 | Identification of a function value | Reading, identifying, naming, or determining one or more isolated function value(s) from a graph. The values are considered independently and are not connected to one another. No further classification, interpretation, contextualization, explanation, or argumentation is required. |   "Based on B2, state the equilibrium volume fraction of ammonia at:<br>(a) 400 °C; 20 MPa<br>(b) 400 °C; 60 MPa<br>(c) 300 °C; 30 MPa<br>(d) 500 °C; 30 MPa"<br>(*Klett H*, p. 109) |
| Level 2 | Description of graphs | Reading, identifying, describing, calculating, or comparing at least two function values or one or more graphs, typically from experimental or time-dependent data. No further classification, interpretation, contextualization, explanation, or argumentation is required. |   "Describe the two energy profiles shown in (a) and (b) using technical terms [. . .]" (*Buchner H1*, p. 118) |
| Level 3 | Interpretation of a function value | Classifying, interpretating, contextualizing, explaining, justifying, or calculating one or more isolated function value(s) from a graph, going beyond mere identification (Level 1). The values are considered independently and are not connected to one another. Students analyze the value in depth, applying domain-specific knowledge to interpret its significance, or connect it to underlying chemical principles. |   "Explain the location and number of equivalence points" (*Westermann H*, p. 185) |
| Level 4 | Interpretation of one graph | Classifying, interpretating, contextualizing, explaining, justifying, or formulating hypotheses regarding one graph within a chemical context. Students analyze the graph in depth, applying domain-specific knowledge to interpret its significance, justify trends, or connect it to underlying chemical principles. |   "Explain the increasing trend of the curve" (*Westermann H*, p. 122) |
| Level 5 | Interpretation of more than one graph | Classifying, interpretating, contextualizing, explaining, justifying, or formulating hypotheses regarding at least two graphs within a chemical context. Students compare and analyze the graphs in depth, applying domain-specific knowledge to interpret their significance, justify trends, or connect them to underlying chemical principles. |   "Formulate a hypothesis regarding whether PET and PU are thermoplastics or thermosets" (*Westermann L*, p. 366) |

skills and a domain-specific understanding of representational conventions.

### The role of textbooks in learning with graphs

Textbook content is typically shaped by the core curriculum (Stöber, 2010; Doll *et al.*, 2012). Accordingly, textbooks serve as close representations of the implemented curriculum across different school subjects (Good, 1993; Fan, 2013; Fan *et al.*, 2013; Khaddoor *et al.*, 2017; Upahi and Ramnarain, 2019). Analyzing chemistry textbooks therefore provides valuable insights into the content likely addressed during classroom instruction (Ring and Brahm, 2020). As national curricula differ, textbook content also varies accordingly.

Textbooks play a central role for both students and teachers. For students, they serve as essential learning resources that enable flexible, self-paced access to content and support individual learning (Roth *et al.*, 1999; Bowen and Roth, 2002; Aydin *et al.*, 2014; Rusek and Vojíř, 2019; Tang, 2023a; Chi *et al.*, 2024). Consequently, it is essential that textbooks are designed to be as accessible and comprehensible as possible to effectively support student learning. For teachers, textbooks are essential tools for lesson planning and instruction, providing a primary source of information (Good, 1993; Upahi and Ramnarain, 2019; Meyer and Pietzner, 2022; Vojíř and Rusek, 2022). Due to their close alignment with classroom practice, textbooks serve as important indicators of instructional implementation (Papageorgiou *et al.*, 2019).

Visual representations in science textbooks play a crucial role in learning, as they are frequently used and considered a major source of information alongside text (Bowen and Roth, 2002). As part of the textbook's broader didactic equipment, they actively shape the learning process (Rusek *et al.*, 2020). Numerous studies have examined the use of visual representations in textbooks, either broadly (*e.g.*, Bowen and Roth, 2002; Kapıcı and Savaşcı-Açıkalın, 2015; LaDue *et al.*, 2015; Upahi and Ramnarain, 2019; Tang, 2023a, 2023b), or with specific focus on graphs (*e.g.*, Roth *et al.*, 1999; Ring and Brahm, 2020), with realistic pictures and graphs consistently identified as among the most common types (LaDue *et al.*, 2015). Despite their prevalence, knowledge about how graphs are actually employed in chemistry textbooks remains limited. As Upahi and Ramnarain (2019, p. 146) note, "the credibility of the information [including visual representations] offered in the textbooks should be of major concern to researchers and science educators." Addressing this research gap, the present study provides foundational insights into the use of graphs in German chemistry textbooks, contributing to a deeper understanding of their educational role and effectiveness.

As the structure and content of textbooks are closely aligned with national educational frameworks, it is essential to understand the organization of the German school system and the positioning of chemistry within it. The following section therefore provides a brief overview of the German school structure to contextualize the textbook analysis.

### Overview of the german school system

The German school system is multi-tiered and divided into different types of schools. Student academic performance determines progression into one of the following school types: *Hauptschule* (secondary general school, offering lower secondary education), *Realschule* (middle school, offering lower secondary education), *Gymnasium* (grammar school, offering both lower and upper secondary education), or *Gesamtschule* (comprehensive school, offering both lower and upper secondary education, and functionally resembling a U.S. high school in terms of structure and inclusivity). While *Hauptschulen*, *Realschulen*, and *Gymnasien* lead to distinct qualifications, *Gesamtschulen* accommodate students of all academic levels and offer the same state-recognized certifications as the traditional school types, depending on students' chosen course of study and performance (Risch, 2010; Döbert, 2015).

The structure and duration of secondary education vary across federal states, typically spanning grades 5/7 to 9/10 or 12/13 (Risch, 2010; Döbert, 2015). In North Rhine-Westphalia – the federal state in which this study was conducted and from which the analyzed textbooks originate – chemistry is introduced in grade 7 and continues through grade 12 or 13, depending on whether the school follows the G8 or G9 curriculum (Döbert, 2015). In Germany, the natural sciences – biology, chemistry, earth science, and physics – are taught as separate subjects from lower secondary level onward. Consequently, chemistry textbooks focus exclusively on chemistry content. This disciplinary focus is a strength of the present study, as it enables the analysis of domain-specific representations without overlap from other sciences. To ensure alignment with current curricular standards, only textbooks published after the 2005 reform of science education were included (Ministerium für Schule und Bildung des Landes Nordrhein-Westfalen, 2011, 2019, 2022). In Germany, textbook approval for classroom use lies within the responsibility of individual federal states, while within schools, subject departments, administrative bodies, and/or teaching staff decide which textbooks to use; ultimately, individual teachers determine the extent to which they incorporate them into their instruction (Stöber, 2010; Barke *et al.*, 2018). Each school type employs textbooks tailored to its specific curricular requirements.

## Methodological approach

To address the research question, a systematic coding approach was employed, guided by a structured category scheme and informed by the method of graphical analysis (Slough *et al.*, 2010; Khine and Liu, 2017). Building on this established approach, we developed an adapted graphical analysis procedure tailored to our research aim, enabling a systematic and structured analysis of both graphs and realistic pictures in the textbooks. Eight German chemistry textbooks served as the data source. The following section outlines the sample selection and the analytical procedure.

### Sample selection

To ensure a diverse and representative sample, textbooks were purposively selected from three major German publishers with nationwide distribution, covering both lower and upper secondary education (*e.g.*, Creswell, 2009; Aeppli *et al.*, 2023). The sample includes textbooks from two school types: middle schools ($N = 2$) and grammar schools at both lower ($N = 3$) and upper secondary levels ($N = 3$). One textbook per educational level was chosen from each publisher (*Klett*, *Westermann*, and *C.C.Buchner*), enabling comparisons across publishers and school types. Specifically, the sample consists of the following textbooks:

- Lower secondary textbooks (grammar schools): *Elemente Chemie* 7–10 (abbr.: *Klett L), Chemie Gesamtband Sekundarstufe I* (abbr.: *Buchner L*), and *Chemie heute* (abbr.: *Westermann L*)

• Lower secondary textbooks (middle schools): *Prisma Chemie 1/2* (abbr.: *Prisma*), and *Blickpunkt Chemie* 7–10 (abbr.: *Blickpunkt*)

• Upper secondary textbooks (grammar schools): *Elemente Chemie Oberstufe* (abbr.: *Klett H*), *Chemie Einführungsphase* (abbr.: *Buchner H1*), *Chemie Qualifikationsphase* (abbr.: *Buchner H2*), and *Chemie heute SII* (abbr.: *Westermann H*)

Including textbooks from major publishers and across multiple school types and levels ensures that the sample likely represents materials widely used by chemistry teachers, offering authentic insights into the use of graphs across educational contexts. The only exceptions were that *C.C. Buchner* currently does not offer a middle school textbook, and its upper secondary textbook is divided into two volumes (abbreviated as *Buchner H1* and *Buchner H2*), which were analyzed jointly to maintain comparability.

### Data analysis

The process of the adapted graphical analysis comprised three main steps, with further details and adaptations for each sub-research question provided below. First, visual representations relevant to the research question were identified and defined. Second, a codebook was developed to ensure coding consistency and clarity. Third, intercoder reliability was assessed for SQ4. The full category scheme is presented in Appendix Table 10; an example of the applied coding (from the 3550 visual representations) is shown in Table 2.

Each textbook was analyzed in full, examining every page and chapter systematically to ensure comprehensive coverage. Both analog and digital formats (*e.g.*, QR codes linking to digital visual representations) were included. For SQ1, all visual representations, including graphs, realistic pictures, and mixed forms (visual representations combining elements of both), were identified, counted, photographed, and logged by page (category: ''Page'') and type (category: ''Visual Representation Type'') to allow direct comparison of usage and frequency. For SQ2, graphs and realistic pictures were further categorized into subtypes (category: ''Visual Representation Subtype''): realistic pictures were coded as Iconic or Schematic, and graphs as line graphs, column charts, bar graphs, scatter plots, pie charts, scales, or special forms. Representations that could not be clearly assigned to a (sub-)category were labeled ''not classifiable.'' Although SQ2 focuses exclusively on graphs and not on realistic pictures, the latter were nonetheless coded to support a comprehensive understanding of visual representation use and to draw conclusions about mixed types; however, this is beyond the scope of the present paper. To better distinguish the different (sub-)types of visual representations, each category was defined and accompanied by anchor examples to ensure coding consistency (see Table 3; Kuckartz and Rädiker, 2022).

The ''special forms'' subcategory includes visual representations with graphical elements (*e.g.*, a horizontal axis) that do not fully meet criteria for a specific graph type. Non-relevant visual representations, such as geometric figures (*e.g.*, cubes, cylinders), symbols (*e.g.*, GHS hazard pictograms, element symbols, periodic table entries), structural formulas, circuit diagrams, labeled arrows, structural forms, flowcharts, and schematic realistic pictures embedded directly in the text (*e.g.*, *Buchner L*, p. 71) were excluded. Screenshots from animations and simulations embedded directly in the textbook, however, were included, as they typically represent subtypes of realistic pictures.

All identified visual representations were coded using the appropriate code (*e.g.*, a titration graph coded as ''LD''), including both directly visible visual representations and those indirectly accessible, such as tasks requiring students to draw a visual representation (*e.g.*, drawing a titration curve based on a table of values), the latter were coded in parentheses (*e.g.*, ''(LD)''). Purely textual descriptions of visual representations (*e.g.*, general explanations of energy profiles in the text) were not coded. Typically, each caption corresponded to one visual representation. All captions were transcribed manually (category: ''Caption'') and coded as ''no caption'' if absent. Captions also helped identify and assign individual visual representations. When multiple visuals were grouped as a unit – such as within a shared frame, on a chapter cover page, or when two visual representations of the same type appeared under one caption – they were counted as one unit due to their visual interconnection and limited separability. If a caption referred to distinctly different types (*e.g.*, one graph and one realistic picture), these were recorded individually. Combinations of iconic (''I'') and schematic (''S'') realistic pictures were coded

Table 2 Example coding of a visual representation from the textbook analysis (*Westermann H*, p. 390). The figure was taken from the original chemistry textbook and translated into English by the authors

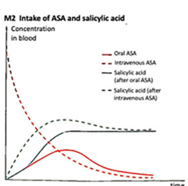
| Number | Page | Figure | Caption | Visual representation type | Visual representation subtype | Content area | Text/task assignment | Competence component (level) | Other |
|---|---|---|---|---|---|---|---|---|---|
| 372 | 390 |  | None | Graph | LD [line graph] | Acids, bases, and analytical methods | AB [task] (''Describe and explain the different curve profiles in M2. [. . .]'') | – Information extraction: description of graphs → Level 2<br>– Information extraction: interpretation of more than one graph → Level 5 | – Interdisciplinary context<br>– Simple axis labels<br>– Differentiation of graphs by color and line type |

Table 3 Overview of analyzed types of visual representations and their subtypes. All textbook examples were taken from the original chemistry textbooks and translated into English by the authors, staying as close as possible to the original terminology

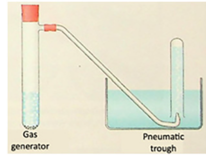
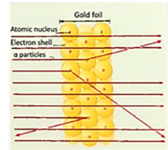
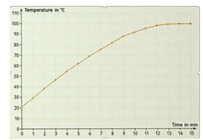
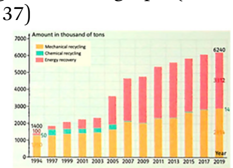
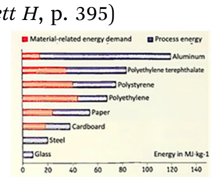
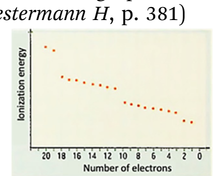
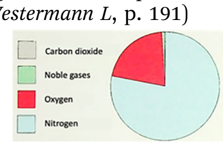
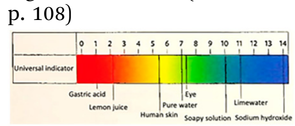
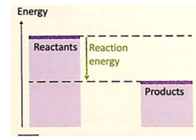
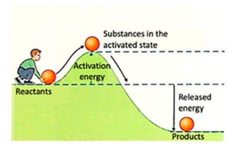
| Visual representation type | Definition (visual representation) | Visual representation subtype | Definition (visual representation subtype) | Textbook example |
|---|---|---|---|---|
| Realistic picture | Visual representations that represent aspects of physical objects or processes (Kosslyn, 2006; LaDue *et al.*, 2015; Tang, 2023a) | Iconic | Pictures that closely resemble real objects and preserve the real-world spatial relationships among depicted elements (Khine and Liu, 2017; Tang, 2023a) | <br>Fig. T3.1 Iconic realistic picture (*Buchner H2*, p. 59) |
| | | Schematic | Simplified or abstract pictures that do not preserve real-world spatial relationships among depicted elements (Khine and Liu, 2017; Tang, 2023a) | <br>Fig. T3.2 Iconic realistic picture (*Klett L*, p. 196) |
| Graph | Visual representations that encode quantitative information by the position and magnitude of geometric elements plotted on Cartesian or polar coordinate axes (Kosslyn, 2006; LaDue *et al.*, 2015; Tang, 2023a) | Line graph | Graphs that display quantitative data points connected by straight lines to show trends or changes over a continuous variable (Kosslyn, 2006) | <br>Fig. T3.3 Line graph (*Klett L*, p. 37) |
| | | Column chart | Graphs that represent categorical data using vertical rectangular bars of equal width; the height of each bar corresponds to the value of the category (Kosslyn, 2006) | <br>Fig. T3.4 Column chart (*Klett H*, p. 395) |
| | | Bar graph | Graphs that represent categorical data using horizontal rectangular bars of equal width; the length of each bar corresponds to the value of the category (Kosslyn, 2006) | <br>Fig. T3.5 Bar graph (*Westermann H*, p. 381) |
| | | Scatter plot | Graphs that display individual data points to show the relationship between two quantitative variables (Kosslyn, 2006) | <br>Fig. T3.6 Scatter plot (*Westermann L*, p. 191) |
| | | Pie chart | Graphs that represent proportional data as segments of a circle, each segment corresponding to a part of the whole (Kosslyn, 2006) | <br>Fig. T3.7 Pie chart (*Prisma*, p. 108) |
| | | Scale | Graphs that show values at regular intervals along an axis | <br>Fig. T3.8 Scale (*Buchner H2*, p. 24) |

Table 3 (*continued*)

| Visual representation type | Definition (visual representation) | Visual representation subtype | Definition (visual representation subtype) | Textbook example |
|---|---|---|---|---|
| | | Special form | Graphs that include graph-like elements (*e.g.*, a horizontal axis) but cannot be fully classified as a specific graph type, often due to missing features such as a second axis |   Fig. T3.9 Special form (*Buchner L*, p. 76) |
| Mixed form | Visual representations that integrate elements of both graph subtypes and realistic picture subtypes | — | — |   Fig. T3.10 Mixed form (*Buchner L*, p. 78) |

as "I + S." Comparable combinations for graphs were coded as "Special forms" (Table 3) if they could not be clearly distinguished, ensuring all complex or ambiguous cases were accurately represented. "Mixed forms" were coded with both subtypes indicated (*e.g.*, "Mixed form (LD + S)"). Some realistic pictures and graphs appeared alongside other types of visual representations, such as photographs or mind maps. Only those visual representations relevant to this study were recorded. When the task description was ambiguous about the required response format of the visual representation, these cases were not coded.

To address SQ3, each visual representation was assigned to a specific content area (category: "Content Area"), based on the structure of the North Rhine-Westphalia chemistry curricula. As each school type follows its own curriculum, content areas are introduced progressively throughout secondary education, shaping the organization of textbooks. The content areas relevant to this study, as defined by the respective curricula, are outlined in Table 4. Visual representations that could not be clearly assigned – such as those found in appendices – were coded as "Other." To ensure consistent and systematic assignment and to avoid subjective or ambiguous classifications, visual representations were classified at the chapter level based on chapter titles, which generally reflect areas of the core curriculum.

Regarding SQ4, the first step distinguished visual representations linked to tasks (coded as "AB") from those linked to texts (coded as "L") within the "Text/Task Assignment" category. For visual representations linked to tasks, the task and associated command word(s) – terms indicating the required cognitive operation – were documented verbatim. Different command words elicit distinct cognitive processes (*e.g.*, "describe" *versus* "explain"; Oleschko and Moraitis, 2012) and underpinned the assignment of competence levels. However, their interpretation can vary considerably among teachers (Nadas *et al.*, 2021), and the perceived cognitive demand depends on the specific task context. Tasks without explicit

Table 4 Content areas by school type in chemistry textbooks

| School type | Content areas |
|---|---|
| Grammar school (lower secondary education) | Substances and their properties<br>Chemical reaction<br>Combustion<br>Metals and metal extraction<br>Elements and their classification<br>Salts and ions<br>Chemical reactions involving electron transfer<br>Molecular compounds<br>Acidic and basic solutions<br>Organic chemistry |
| Middle school | Substances and their properties<br>Energy changes in chemical reactions<br>Air and water<br>Metals and metal extraction<br>Elements and their classification<br>Acids, bases and salts<br>Energy from chemical reactions<br>Substances as energy sources<br>Chemical products |
| Grammar school (upper secondary education) | Organic compound classes<br>Reaction rates and chemical equilibrium<br>Acids, bases, and analytical methods<br>Electrochemical processes and energetics<br>Reaction mechanisms in organic chemistry<br>Modern materials |

reference were also coded if a connection could be identified through content-related links or spatial proximity. Visual representations that could not be linked clearly to either a text or a task – for example, when appearing without direct textual reference and serving a decorative function (*e.g.*, chapter cover pages) were coded as "Unassignable." In a second step, each line-graph-related task was coded for both the competence component (*e.g.*, "Information extraction") and, in the case of information extraction tasks, the corresponding competence level (*e.g.*, "Identification of a function value"). Tasks that could not be clearly assigned were coded as "Not classifiable". Mixed and special forms were excluded from coding (see "Limitations"). Tasks that merely required the reproduction of existing graphs (*e.g.*, copying a graph) were also excluded, as these require minimal cognitive effort.

To ensure coding reliability, two researchers independently coded the competence levels for 20% of the line graph-related tasks ($n$ = 74), discussed discrepancies, and revised definitions, and examples as needed (Guest *et al.*, 2012; Kuckartz and Rädiker, 2022). Remaining disagreements were resolved through a consensus-based approach involving a third researcher. This approach is essential for assessing intercoder agreement and thereby ensuring the trustworthiness and credibility of the research. It addresses key criteria such as dependability, confirmability, credibility, and transferability (Lincoln and Guba, 1985; Lewis and Ritchie, 2003). By minimizing subjectivity and bias, this process strengthens the replicability of the findings and ensures that results genuinely reflect the data, increasing the likelihood that similar outcomes would be obtained in a repeat study using comparable methods (Lewis and Ritchie, 2003). Statistical analyses were conducted using *jamovi* software (Version 2.6) with the *ClinicoPath* module (Gamer *et al.*, 2019; Balci, 2022; The jamovi project, 2024). Intercoder reliability, measured by Cohen's kappa, indicated very high agreement ($\kappa$ = 0.946; Cohen, 1960; Landis and Koch, 1977; McHugh, 2012).

The dataset includes additional categorized elements (*e.g.*, the use of realistic pictures, command words, captions) that may support future research. However, only findings directly relevant to SQ1–SQ4 are reported below. A visual summary of the methodological procedure is provided in Fig. 1.

## Results

The results are presented below, structured to address each sub-question individually.

### SQ1: frequency of graph usage compared to realistic pictures in chemistry textbooks

The distribution of visual representations differed significantly across school types, $\chi^2$ (d$f$ = 4, $N$ = 3550) = 306.00, $p < 0.001$. Post-hoc pairwise chi-square tests with Bonferroni correction (adjusted threshold: $p < 0.017$) confirmed that all three school type comparisons were statistically significant. Specifically, there were significant differences in the distribution of visual representation types between lower secondary grammar and middle school textbooks ($\chi^2$ = 53.0, d$f$ = 2, $p < 0.001$), between lower and upper secondary grammar school textbooks ($\chi^2$ = 113, d$f$ = 2, $p < 0.001$), and between upper secondary grammar and middle school textbooks ($\chi^2$ = 273, d$f$ = 2, $p < 0.001$). Realistic pictures were used significantly more frequently than graphs in all analyzed chemistry textbooks across all school types (see Fig. 2). However, this disparity decreased at the upper secondary level, where the proportion of graphs increased while the use of realistic pictures declined compared to lower secondary textbooks. To strengthen comparability among textbooks with varying page counts, the number of graphs per 100 pages was calculated (see Appendix Table 11). On average, lower secondary textbooks for grammar schools featured 16.1 graphs per 100 pages (SD = 5.92, min = 10.4, max = 22.2, 95% CI [1.37, 30.8]), while lower secondary textbooks for middle schools contain 7.86 graphs per 100 pages (SD = 0.64, min = 7.41, max = 8.31, 95% CI [2.14, 13.6]). Upper secondary textbooks showed the highest density, with an average of 25.0 graphs per 100 pages (SD = 8.47, min = 17.3, max = 34.0, 95% CI [3.94, 46.0]).

These results indicate a clear shift toward more abstract visual representations as students progress through their education. Notably, the two middle school textbooks exhibited a distinct pattern, featuring the highest proportion of realistic pictures (92.36%) and the lowest proportion of graphs (6.16%). Mixed forms were rare at all school levels, with 24 instances in lower secondary (grammar school), 16 in lower secondary (middle school), and 40 in upper secondary textbooks (see Fig. 2).

Publisher-specific differences were also observed (see Appendix Table 11), with *Westermann* containing the highest

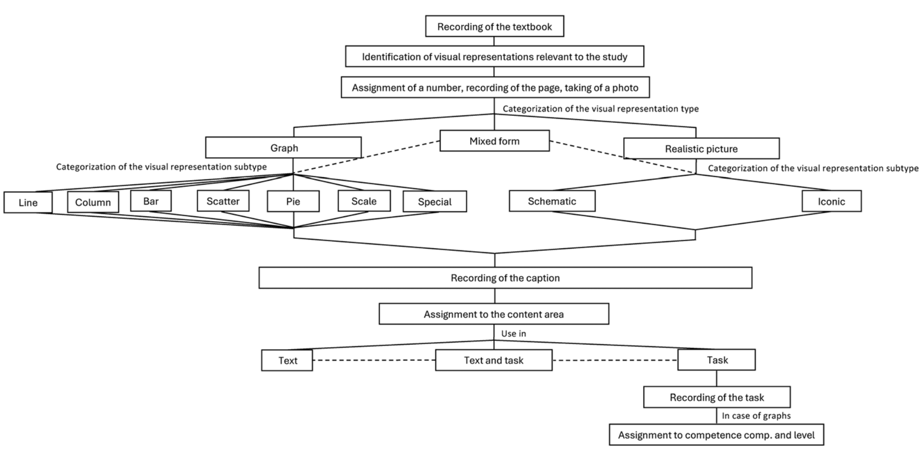



Fig. 1 Visual summary of the methodological approach in the textbook analysis.

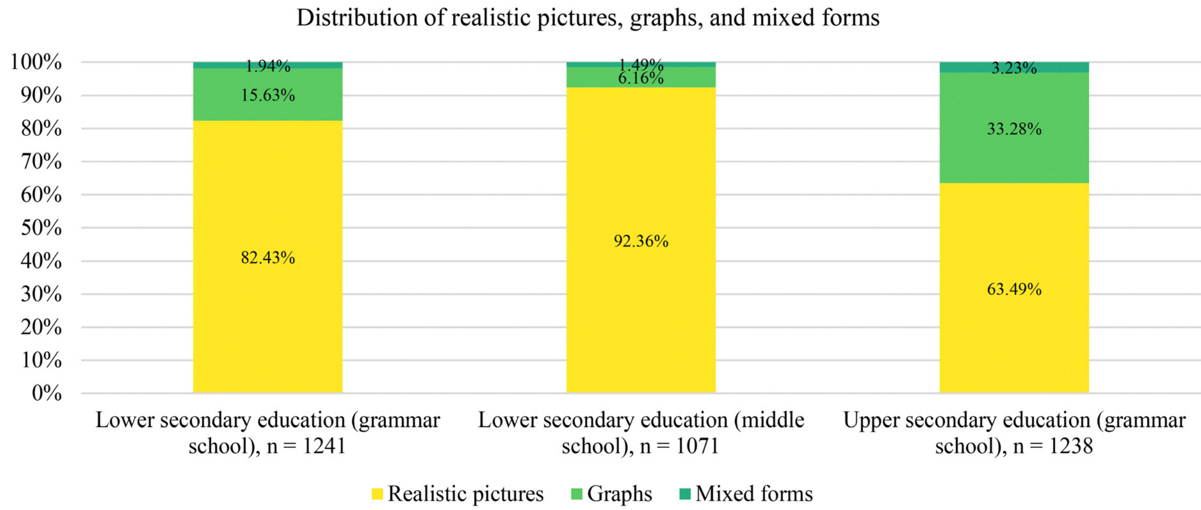



Fig. 2 Percentage distribution of realistic pictures, graphs, and mixed forms by school level. Percentages indicate the proportion of each visual representation type relative to the total number of visual representations within each school type.

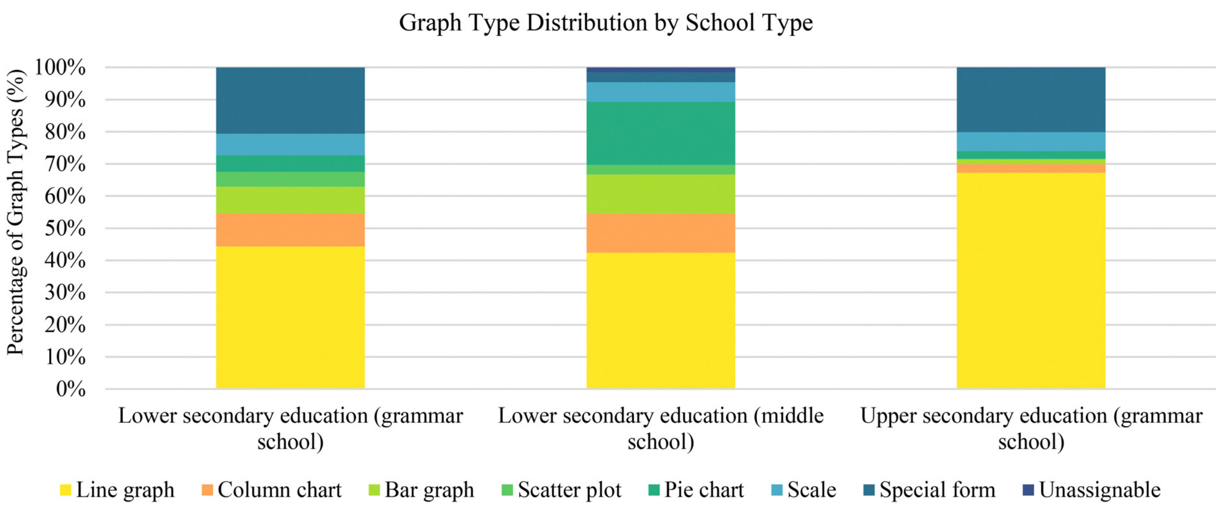



Fig. 3 Percentage distribution of graph types by school level. Percentages indicate the proportion of each graph type relative to the total number of graph types within each school type.

mean number of graphs per 100 pages at both grammar school levels, and *Klett* showing slightly higher graph usage in middle school textbooks. These publisher-specific patterns are discussed further in the ''Discussion'' section.

### SQ2: types of graphs in chemistry textbooks

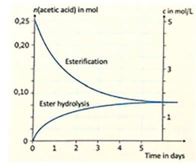
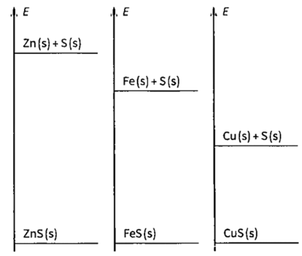
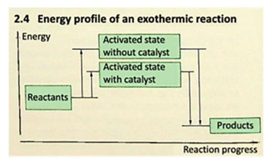
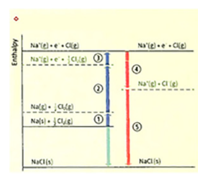
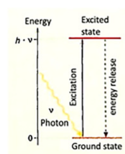
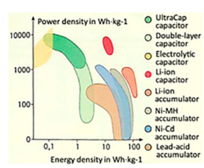
The frequency of graph types varied considerably across the analyzed textbooks (see Appendix Table 12 and Fig. 3).

Across all textbooks, line graphs were used most frequently ($n$ = 391), followed by special forms ($n$ = 121). The latter appeared in all school levels except in middle school textbooks, where only two were identified. In contrast, column charts, bar graphs, scatter plots, pie charts, and scales occurred much less frequently overall.

**Form-related findings.** A closer examination was conducted of graphs categorized as ''special forms,'' which could not be assigned to any standard graph type. These graphs exhibited distinctive features or applications that differed from those in other disciplines and are hereafter referred to as chemistry-specific graphs. Most shared structural similarities with conventional types – particularly line graphs – and with one another. Several chemistry-specific features were identified (see Table 5), though they could not be fully generalized. Many combined multiple features; hence, Table 5 and the following analysis represent a preliminary classification. Notably, characteristics such as embedded reaction equations or structural formulas alongside curves may also appear in other graph types (*e.g.*, line graphs).

Chemistry-specific graphs frequently displayed unique structural and functional features, including multiple vertical axes labeled with different variables (*e.g.*, substance amount ($n$) and substance concentration ($c$) in Fig. T5.1). Structural variation was common, particularly regarding form and complexity, for instance, energy levels were represented as horizontal plateaus connected by arrows indicating transitions. Such

Table 5 Overview of exemplary special features identified in chemistry-specific graphs ("special forms") and corresponding textbook examples. All illustrative textbook examples were taken from the original chemistry textbooks and translated into English by the authors, staying as close as possible to the original terminology

| Identified special feature(s) | Illustrative example from textbook |
| --- | --- |
| Two vertical axes labeled with different variables |   Fig. T5.1 Graph with two vertical axes, each representing a different variable (amount of substance, $n$, and concentration, $c$), plotted over time (*Buchner H1*, p. 129) |
| Three vertical axes displayed side by side, no horizontal axis; plateaus include individual elements of reaction equations |   Fig. T5.2 Graph displaying three vertical axes without a horizontal axis, including plateaus annotated with reaction equation elements (*Westermann H*, p. 125) |
| Plateaus annotated with text fields containing chemical terminology |   Fig. T5.3 Graph showing plateaus, each labeled with chemical terminology in text fields (*Westermann H*, p. 14) |
| No horizontal axis; plateaus include elements of reaction equations and numbered reaction steps, with arrows indicating transitions between plateaus |  Fig. T5.4 Graph without a horizontal axis, showing plateaus annotated with reaction equation elements and arrows indicating different reaction steps (*Westermann H*, p. 147) |
| Multiple lines and curves within a single graph, each with distinct representational meaning |   Fig. T5.5 Graph with multiple lines and curves, each representing a distinct meaning (*Klett H*, p. 350) |
| Logarithmic axes with shaded or marked areas representing power and energy densities |   Fig. T5.6 Graph with logarithmic axes and shaded areas indicating power and energy densities (*Westermann H*, p. 223) |

plateaus or curves were often annotated with additional information, including (parts of) reaction equations (*e.g.*, *Westermann H*, pp. 125, 140, 144, 147; *Klett L*, pp. 297, 455; *Klett H*, pp. 197, 199, 205, 242, 307, 495; *Buchner H2*, p. 210), word equations (*e.g.*, *Buchner L*, pp. 89, 402; *Westermann L*, pp. 90, 91; *Buchner H2*, p. 182), cell potentials (*e.g.*, *Westermann H*, p. 207), or (thermodynamic) data such as solution enthalpy (*e.g.*, *Klett H*, p. 203), formation enthalpy (*e.g.*, *Klett L*, p. 233), and free reaction enthalpy (*e.g.*, *Klett H*, p. 242). Other examples included graphs integrating structural formulas (*e.g.*, *Westermann H*, pp. 269, 304, 323; *Klett H*, p. 323; *Buchner H2*, pp. 362, 467), elements of orbital models (*e.g.*, *Klett H*, p. 326; *Buchner H2*, pp. 339, 350, 351), or textual features such as speech bubbles (*e.g.*, *Westermann L*, pp. 91, 145; *Westermann H*, p. 332) and text fields (see Fig. T5.3; *Westermann H*, p. 14; *Klett L*, p. 153; *Buchner L*, p. 197). Arrows between energy levels were sometimes annotated with technical terms like lattice energy, heat of solution, intermediates, or mesomeric energy.

Several chemistry-specific graphs illustrated multi-step processes, with individual steps numbered sequentially (see Fig. T5.4; *e.g.*, *Westermann H*, pp. 147, 239, 269, 304; *Blickpunkt*, p. 241). In some cases, multiple possible reactions were compared within a single graph, for example, a graph contrasting energy differences between (a) the direct reaction of copper(II) ions with zinc, (b) the reaction in a Daniell cell without applied current, and (c) the reaction in a Daniell cell with applied current (*Klett H*, p. 242). Another notable characteristic was the use of distinct curve styles to convey meaning. For instance, in graphs depicting the excited state of a molecule (*e.g.*, in spectroscopy or quantum mechanics), a wavy line indicated photon emission, a solid line represented electron excitation from ground state to excited state, and a dashed line showed the energy released during emission (*e.g.*, *Klett H*, pp. 350, 361). These conventions illustrate how discipline-specific design choices are employed in chemistry textbooks, both in overall composition and in individual curve representation. Fig. T5.1–T5.6 (Table 5) present selected examples that highlight these distinctive graphical features. Across all textbooks, the number of chemistry-specific graphs increased from lower ($n$ = 42) to upper secondary textbooks ($n$ = 77), indicating that, with rising grade level, not only did the subject matter become more specialized, but the graphical representations themselves also grew in structural complexity.

**Content-related findings.** From a content perspective, a closer examination revealed that energy profile graphs were particularly prominent across chemistry topics, suggesting they serve as a central means of visualizing abstract concepts such as energy and energy changes in chemical processes. The analysis further showed that the term "energy profile" functions as an umbrella term, referring to several graph variants depending on the represented content. Fig. T6.1–T6.3 in Table 6 illustrate this diversity, presenting three examples of energy profiles that emphasize different aspects according to the underlying chemical phenomena. This points to a notable interplay between the graphical representation and the chemical content visualized.

**Language-related findings.** Several linguistic characteristics became apparent in the textbook sample, especially regarding naming conventions. Some graph names were compound terms derived from axis labels – for instance, in *Westermann H*: "time-temperature graph," "time-current graph," "current-substance quantity graph," "voltage-current graph" (all examples from *Westermann H*, p. 243), and "concentration–extinction diagram" (*Westermann H*, p. 351). While systematic, it presupposes that readers are familiar with the underlying scientific concepts (*e.g.*, "current," "amount of substance," "voltage," "extinction"). Another linguistic issue concerns the German word "Diagramm," which corresponds to the English word "graph" (see "Theoretical Background"). Certain terms, such as "Zelldiagramm" (*e.g.*, *Westermann H*, p. 207, *Buchner H2*, p. 124), translate literally as "cell graph," but refer to a symbolic arrangement rather than an actual graph, revealing a mismatch between the term's semantics and the representation itself.

The analysis also revealed a graph-specific language register. For example, *Westermann H* (p. 241; emphasis added) states: "in the graph, the amounts of substance $n$ formed during electrolysis are plotted *against* the charge Q that has passed." Another passage reads: "At sufficiently low concentrations, the graphical representation of the extinction *as a function of* concentration (*concentration–extinction graph*) *yields a straight line* with a *slope* $\varepsilon\lambda\cdot d$, from which the concentration of the colored substance in an unknown solution *can be read directly*" (*Westermann H*, p. 351; emphasis added). Such examples illustrate the use of specialized graph language, encompassing both chemistry-specific terminology and the linguistic conventions for describing and interpreting graphs.

Furthermore, visual representations in textbooks are often labeled imprecisely or inconsistently. Graphs (*e.g.*, *Buchner H1*, pp. 156, 177; *Westermann H*, p. 123), tables (*e.g.*, *Westermann H*, p. 184), and structural formulas (*e.g.*, *Westermann H*, p. 284) were frequently grouped under the generic term "illustrations" (German: "Abbildungen") without specifying the representational type. Terminological variation was also observed: line graphs (German: "Liniendiagramme") were sometimes referred to as such but elsewhere described as "curve graphs" (German: "Kurvendiagramme"; *e.g.*, *Blickpunkt*, p. 139), similar inconsistencies appeared with "bar graphs" (German: "Balkendiagramme"; *e.g.*, *Buchner L*, p. 157) and "striped graphs" (German: "Streifendiagramme"; *e.g.*, *Blickpunkt*, p. 139). Overall, the findings indicate that graph use in chemistry textbooks encompasses a distinct *linguistic* dimension. All dimensions, the formal, the conceptual and the linguistic, must be addressed to enable successful comprehension of and communication about graphs in chemistry.

### SQ3: graphs across different content areas

Graphs play a central role in chemistry education, appearing across all content areas and school types. Their varied forms and functions highlight their cross-curricular relevance within the discipline. However, their frequency and purpose vary by school type. In lower secondary grammar school textbooks, graphs occurred most frequently in the content area of "Chemical reaction," for example when illustrating changes in activation energy with and without a catalyst (see Table 7).

Table 6 Overview of different energy profiles in chemistry textbooks. All illustrative textbook examples were taken from the original chemistry textbooks and translated into English by the authors, staying as close as possible to the original terminology

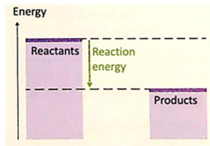
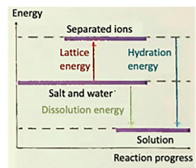
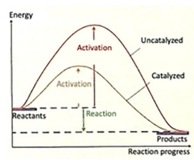
| Visual emphasis | Illustrative example from textbook |
|---|---|
| Energy profile 1 – Reaction energy (bar representation) | <br> |
| This energy profile depicts the energy levels of reactants and products as bars in the context of an exothermic reaction. The bar representing the reactants is positioned higher than that of the products, visually emphasizing the decrease in energy during the reaction. The graph highlights the overall reaction energy but omits the detailed energy pathway and transition state. | Fig. T6.1 Energy profile illustrating the energy levels of reactants and products in an exothermic reaction. The higher bar for reactants and the lower bar for products visually emphasizes the energy decrease during the reaction (Buchner L, p. 76) |
| Energy profile 2 – Solution process (multiple sub-steps) | <br> |
| This energy profile illustrates the dissolution of a salt in water and emphasizes that the process consists of multiple energetic sub-steps. Lattice energy must be supplied (endothermic), whereas hydration energy is released (exothermic). The overall solution energy results from the balance of these two contributions, determining whether the process is energetically favorable. The graph underscores that dissolving a salt involves a sequence of opposing energy changes rather than a single energy conversion. | Fig. T6.2 Energy profile representing the solution process of a salt in water, showing both endothermic (lattice energy) and exothermic (hydration energy) sub-processes. The graph emphasizes the balance of these opposing energy changes (Buchner L, p. 285) |
| Energy profile 3 – Catalysis and activation energy (process-focused) | <br> |
| This energy profile represents an exothermic reaction and highlights the influence of activation energy on the reaction pathway. It contrasts the energy pathways of catalyzed and uncatalyzed reactions, emphasizing that a catalyst lowers the activation energy while leaving the overall reaction energy unchanged. The focus of this representation is on the energetic *process* itself rather than on the discrete energy states of reactants and products. | Fig. T6.3 Energy profile illustrating the effect of a catalyst in lowering the activation energy of an exothermic reaction (Buchner L, p. 291) |

Table 7 Distribution of graphs across content areas in lower secondary education textbooks (grammar school)

| Content area | Number of graphs |
|---|---|
| Substances and their properties | 21 (10.83%) |
| Chemical reaction | 41 (21.13%) |
| Combustion | 20 (10.31%) |
| Metals and metal extraction | 10 (5.15%) |
| Elements and their classification | 20 (10.31%) |
| Salts and ions | 15 (7.73%) |
| Chemical reactions involving electron transfer | 7 (3.61%) |
| Molecular compounds | 22 (11.34%) |
| Acidic and basic solutions | 7 (3.61%) |
| Organic chemistry | 31 (15.98%) |
| Total | 194 |

Table 8 Distribution of graphs across content areas in lower secondary education textbooks (middle school)

| Content area | Number of graphs |
|---|---|
| Substances and their properties | 7 (10.61%) |
| Energy changes in chemical reactions | 2 (3.03%) |
| Air and water | 37 (56.06%) |
| Metals and metal extraction | 2 (3.03%) |
| Elements and their classification | 1 (1.52%) |
| Acids, bases and salts | 3 (4.54%) |
| Energy from chemical reactions | 3 (4.54%) |
| Substances as energy sources | 10 (15.15%) |
| Chemical products | 1 (1.52%) |
| Total | 66 |

In middle school textbooks, graphs appeared predominantly in the unit ''Air and water,'' often used to depict air composition or visualize $CO_2$ emissions (see Table 8).

At the upper secondary level, graphs were most frequently employed in the content area ''Reaction rates and chemical equilibrium,'' where they represented the progression of chemical reactions (*e.g.*, reaction speed) and visualized

Table 9 Distribution of graphs across content areas in upper secondary education textbooks (grammar school)

| Content area | Number of graphs |
|---|---|
| Organic compound classes | 17 (4.13%) |
| Reaction rates and chemical equilibrium | 102 (24.76%) |
| Acids, bases, and analytical methods | 93 (22.57%) |
| Electrochemical processes and energetics | 96 (23.30%) |
| Reaction mechanisms in organic chemistry | 85 (20.63%) |
| Modern materials | 9 (2.18%) |
| Other | 10 (2.43%) |
| Total | 412 |

abstract concepts such as the Boltzmann distribution (see Table 9).

These findings demonstrate that graph use in chemistry textbooks is clearly content-dependent. The selection of graph type, its specific form, and its function are driven by the subject matter being represented, with particular graph types serving as standard tools for specific content domains. For instance, line graphs are used almost exclusively in the ''Reaction rates and chemical equilibrium'' unit at the upper secondary level, reflecting their central role in teaching these topics. Notably, all analyzed textbooks display graphs of comparable structure in similar content domains, suggesting the presence of domain-specific graphical prototypes – standardized representational forms that recur across textbooks. Typical examples include equilibrium graphs in the context of chemical equilibrium (see Fig. 4), titration curves in acid–base chemistry, and boiling point comparison graphs in organic chemistry.

Although certain graph types are typically associated with specific content areas – such as energy profiles in the ''Chemical reaction'' domain – they also appeared in other contexts, such as ''Molecular compounds,'' where they served comparable purposes (*e.g.*, visualizing energy changes in chemical processes). This indicates that particular graph types fulfill cross-curricular representational functions, acting as unifying elements throughout the chemistry curriculum. Furthermore, the results show that, despite content-specific adaptations, graphs were frequently integrated with experimental activities across all textbooks, demonstrating the connectedness of graphical representations with experimental engagement within chemistry. In summary, graphs in chemistry textbooks serve as both content-specific and content-linking elements.

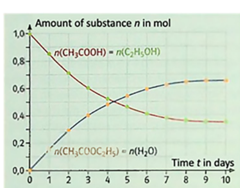



Fig. 4 A prototypical graph of chemical equilibrium, illustrated by the esterification and hydrolysis of ethyl acetate. The example was taken from the original chemistry textbook and translated into English by the authors, staying as close as possible to the original terminology (*Klett H*, p. 100).

### SQ4: graph-related tasks, competence components and competence levels

The findings showed that in lower secondary education (both grammar and middle school textbooks), the competence components ''Information extraction'' and ''Construction'' occurred with comparable frequency, with ''Construction'' appearing slightly more often. This balance shifted at the upper secondary level, where ''Information extraction'' predominates in graph-related tasks (see Fig. 5).

Analysis of competence levels indicated that, across all school types, every graph-related task could be assigned to a specific level, revealing distinct patterns across educational levels (see Fig. 6).

In lower secondary textbooks, most tasks targeted competence level 2 (''Description of graphs''), focusing on describing graphical data. In contrast, upper-secondary grammar school textbooks included a higher proportion of cognitively demanding tasks (levels 3–5), requiring explanation and interpretation. In both lower secondary textbooks, the majority of tasks addressed descriptive cognitive operations (levels 1–2), whereas tasks requiring explanation and interpretation (levels 3–5) occurred far less frequently, especially in middle school textbooks. This imbalance indicates that, while descriptive graph skills were systematically fostered in lower secondary education, there was comparatively limited emphasis on developing advanced explanatory and interpretive skills at this stage.

## Discussion

To ensure coherence, the discussion mirrors the structure of the results section and is organized into four subsections, each addressing a sub-question.

### SQ1: frequency of graph usage compared to realistic pictures in chemistry textbooks

In general, the findings show that the prevalence and complexity of visual representations in chemistry textbooks vary by target audience and educational level. Realistic pictures are the most prevalent visual representations in the analyzed chemistry textbooks, outnumbering graphs at both lower and upper secondary levels. This dominance is particularly pronounced in lower secondary textbooks, where the accessibility and immediate recognizability of realistic pictures are especially valuable for students. Iconic realistic pictures, which typically depict chemical phenomena at the macroscopic level, have been shown "to attract, stimulate and sustain students' interest in chemistry" (Upahi and Ramnarain, 2019, p. 153). For younger learners or those with limited prior knowledge, realistic pictures are often more accessible than graphs, which involve multiple layers of abstraction, hindering accessibility and increasing cognitive demands, potentially leading to *cognitive overload* (Sweller, 2005) – or, in Rau's (2017) terms, a *representational dilemma*, where students are expected to learn content they do not yet understand from representations they do not yet comprehend.

Although realistic pictures dominate overall, graphs are nonetheless frequently used in the textbooks analyzed – reflecting

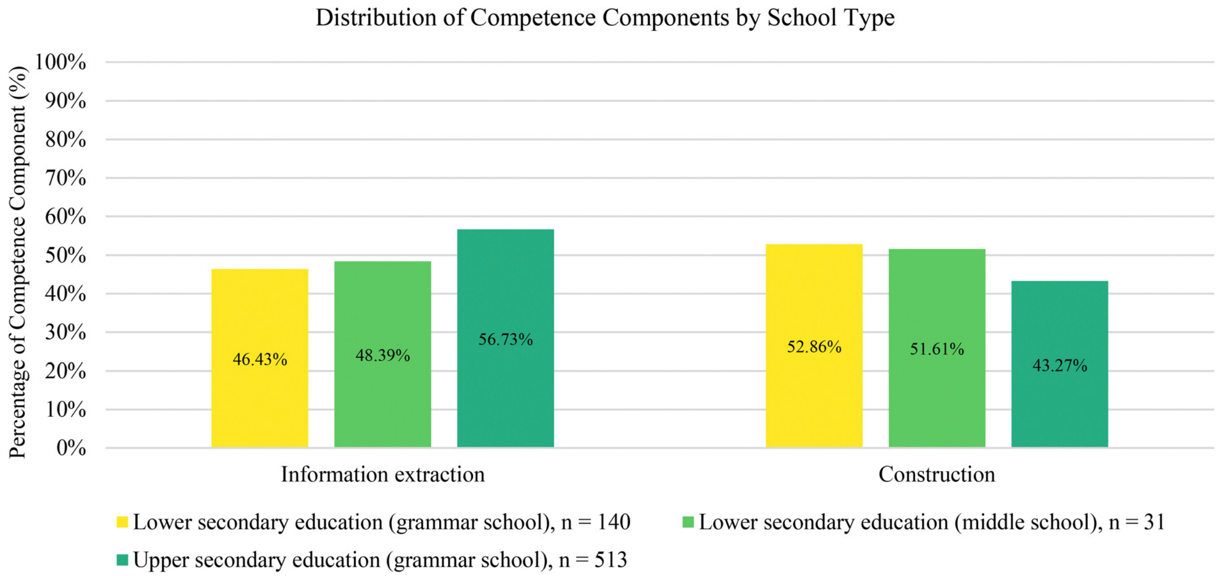



Fig. 5 Percentage distribution of competence components in graph-related tasks by school type. Percentages represent the proportion of each competence component relative to the total number of competence components within each school type. One unclassifiable graph in lower secondary education (grammar school) was excluded from this visualization.

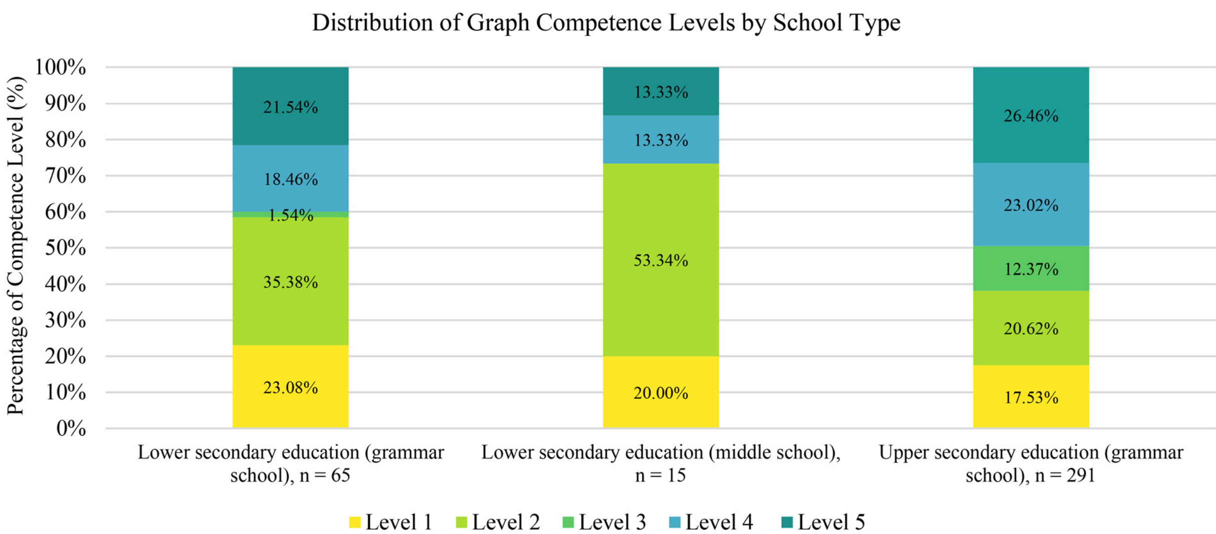



Fig. 6 Percentage distribution of graph-related tasks by competence level and school type. Percentages indicate the proportion of tasks within each competence level relative to the total number of tasks analyzed for each school type. Competence levels are defined as follows: level 1: "Identification of a function value"; level 2: "Description of graphs"; level 3: "Interpretation of a function value"; level 4: "Interpretation of one graph"; level 5: "Interpretation of more than one graph".

efforts to align classroom instruction with authentic scientific practice and underscoring the importance of introducing graphs early to lay a foundation for later abstraction (Krohn, 1991). The higher frequency of graphs in upper secondary textbooks likely reflects curricular demands, as upper-level chemistry topics lend themselves more readily to graphical representation but also assumes a certain level of students' cognitive readiness.

The results also show that mixed forms appear to be comparatively rare, suggesting that clearly distinguishable and unambiguous forms of realistic pictures and graphs are preferred. Such clarity likely supports students in developing stable cognitive schemata by simplifying the distinction between representational forms (Pinker, 1990; Padilla *et al.*, 2018) and reducing cognitive load (Sweller, 2005) – an especially important consideration for novice learners. Conversely, frequent use of mixed or ambiguous forms may hinder schema formation by introducing interpretive ambiguity and additional cognitive effort. The pedagogical implication is that prioritizing clarity over hybridity in visual representations may facilitate comprehension and long-term learning by minimizing unnecessary cognitive demands on students.

Our study reveals considerable variation in the use of graphs both within textbooks of the same school type and grade level (*e.g.*, among different grammar or middle schools), as well as between different types of schools (grammar *versus* middle schools). Such disparities warrant critical attention, as they suggest that opportunities for developing graph competence may depend not only on curricular level but also on school type and publisher. In line with Rusek and Vojíř (2019), who concluded that ''learning outcomes may differ significantly when different books are used, despite the fact that they are supposed to support the same curriculum'' (p. 85), our findings highlight the need for greater consistency in textbook design to ensure equitable learning opportunities. The particularly low frequency of graphs in middle school textbooks is noteworthy, as the ability to interpret and construct graphs is essential not only for understanding scientific phenomena but also for informed participation in societal discourse.

A promising strategy for enhancing graph competence is the inclusion of dedicated methodology pages, which can provide explicit, learner-oriented guidance on fundamental tasks, such as interpreting and constructing graphs in digital and analog formats, thereby addressing all facets of graph competence (Cheung and Slavin, 2013). While beneficial at all educational levels, such pages are particularly valuable in lower secondary education, where foundational skills that underpin later graph use are first developed.

### SQ2: types of graphs in chemistry textbooks

Line graphs are by far the most frequently used graph type in the analyzed chemistry textbooks ($N$ = 391). This predominance aligns with previous research indicating that learners generally find line graphs more familiar and easier to interpret than other graph forms (Leinhardt *et al.*, 1990; Bowen and Roth, 2005; Von Kotzebue *et al.*, 2015). However, this familiarity can also lead to misconceptions, such as the expectation of students that all data points in a line graph should be in line, suggesting unambiguous trends (Bowen and Roth, 2005), a tendency to focus on describing $x$–$y$ trends (Shah *et al.*, 1999), difficulties with interpreting graphs containing multiple lines (Shah and Carpenter, 1995), limited ability to select appropriate graph types (Lachmayer, 2008), and difficulties differentiating between various graph types (Stoczynski *et al.*, 2026). The frequent use of line graphs in textbooks may reinforce these assumptions, potentially limiting students' understanding of variability and complexity in scientific data. Therefore, students should be exposed to a variety of graph types to build comprehensive graph competence (Rybarczyk, 2011).

A closer examination reveals the use of different line types – such as solid, dotted, and dashed lines – to convey distinct meanings. Typically, a solid line connects measured data points, whereas dotted or dashed lines represent hypothetical, extrapolated, or calculated values. For example, Fig. 7 displays the boiling temperatures of various hydrogen compounds ($H_2O$, $H_2S$, $H_2Se$, $H_2Te$), where the solid line represents measured boiling points and the dotted line indicates hypothetical trends. Similarly, Fig. 8 illustrates the graphical determination of a temperature difference using three line types: the dotted line shows measured temperature data, whereas the solid line and the dashed line are used to graphically determine the temperature difference ($\Delta\vartheta$) by means of extrapolation. Differentiating between line styles is therefore essential for accurate interpretation and for distinguishing between empirical findings and theoretical or inferred information.

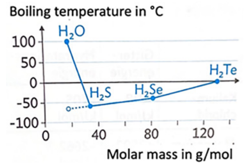



Fig. 7 Solid and dotted lines in a graph showing measured and hypothetical boiling temperatures of hydrogen compounds of main group VI elements ($H_2O$, $H_2S$, $H_2Se$, $H_2Te$). The solid line represents measured data; the dotted line indicates hypothetical values. The example was taken from the original chemistry textbook and translated into English by the authors (*Buchner L*, p. 286).

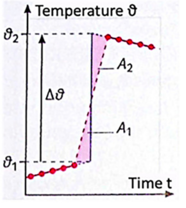



Fig. 8 Solid, dotted, and dashed lines in a graph illustrating the graphical determination of a temperature difference. The dotted line shows measured temperature data, whereas the solid line and the dashed line are used to graphically determine the temperature difference ($\Delta\vartheta$) by means of extrapolation. The example was taken from the original chemistry textbook and translated into English by the authors (*Klett H*, p. 200).

An example of potentially misleading line usage is shown in Fig. 9, which depicts the esterification reaction. The graph shows the change in the amount of substance ($n$, in mol) for acetic acid ($CH_3COOH$) and ethanol ($C_2H_5OH$) (red line with green dots, decreasing) and for ethyl acetate ($CH_3COOC_2H_5$) and water ($H_2O$) (blue line with yellow dots, increasing) over time. The use of dots in one color overlaid on continuous lines in another color creates the misleading impression that, for instance, the amount of substance of ethanol was measured only at discrete time points, while that of acetic acid was measured continuously. In reality, the quantities of both substances decrease at the same rate and should therefore be represented equivalently; the same applies to the ethyl acetate and water, but in reverse. To reflect these simultaneous changes more accurately, a single- or dual-colored line would be preferable. Furthermore, to ensure accessibility and inclusion, red-green color combinations should be avoided, as they may hinder perception for students with color vision deficiencies.

Unfamiliarity with these graphical conventions may lead students to misinterpret line meaning – for instance, confusing measured data with hypothetical trends – underscoring the need for explicit instruction on line types, the simultaneous use of multiple lines, and the distinction between connected and discrete data points. Instruction should also explicitly address the relationship between graph steepness and the corresponding

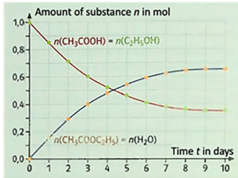



Fig. 9 Changes in the amounts of acetic acid ($CH_3COOH$) and ethanol ($C_2H_5OH$) (red line with green dots, decreasing) and for ethyl acetate ($CH_3COOC_2H_5$) and water ($H_2O$) (blue line with yellow dots, increasing) during esterification over time. Although the amounts of all substances were measured equivalently, the use of dots on the lines may create a misleading impression. For clarity and accessibility, consistent line styles and color choices are recommended. The example was taken from the original chemistry textbook and translated into English by the authors, staying as close as possible to the original terminology (*Klett H*, p. 100).

conceptual schema (Planinic *et al.*, 2012; Rodriguez *et al.*, 2019, 2020). Another challenging convention concerns arrows, whose interpretation is known to pose difficulties for students (Graulich, 2015; Wright *et al.*, 2018). The meaning of arrows can differ depending on context: in everyday representations, arrows typically indicate dynamic processes, such as movement, flow, or transformation, and students often use them in this way (Heiser and Tversky, 2006; Cheng and Gilbert, 2015). In contrast, in chemistry, particularly in special graph forms, arrows often serve different functions, such as representing differences in energy levels between reactants and products or indicating the magnitude and direction of energy changes, such as activation energy or enthalpy differences, rather than depicting a dynamic process (see Fig. 10). Given the importance of consistent visual conventions for comprehension, this divergence may pose a learning challenge. Explicitly addressing these differences through clear legends, explanations, and guided practice can help prevent misconceptions and support the development of graph competence.

Moreover, the predominance of line graphs in chemistry textbooks reflects a focus on visualizing processes – such as changes in temperature or concentration – rather than presenting final products. This process-oriented approach also appears in schematic pictures, which often depict dynamic changes, such as the dissolution of salt in water. This connection becomes particularly apparent in mixed visual representations,

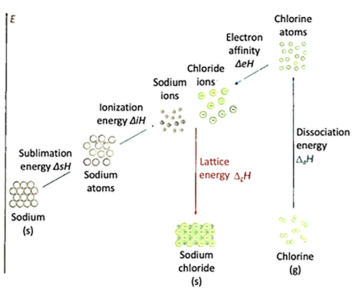



Fig. 10 Hybrid representation combining a graph (scale) and a schematic realistic picture to visualize the sub-steps of sodium chloride synthesis. The example was taken from the original chemistry textbook and translated into English by the authors, staying as close as possible to the original terminology (*Buchner H2*, p. 210).

such as the one shown in Fig. 10, where a scale displaying energy changes along a reaction pathway is combined with schematic pictures of the arrangement of atoms, ions, or molecules at each stage. By integrating both graphical and schematic elements, such hybrids help students understand not only quantitative changes (*e.g.*, energy levels) but also the underlying molecular processes at the submicroscopic level.

When textbooks present mixed forms of graphs and realistic pictures, it is essential that teachers explicitly guide students in distinguishing between these visual representations and in understanding their relationships. Without such support, students may develop alternative conceptions (Kapıcı and Savaşcı-Açıkalın, 2015).

The analysis revealed that the prevalence of special graph forms increases from lower to upper secondary levels, reflecting the growing complexity of visual representations as students progress. These types are often highly complex due to a triple abstraction comprising abstract chemical content, abstract visual form, and abstract chemical terminology. Additionally, as these representations are unfamiliar from other subjects or everyday contexts, students may not yet have developed the cognitive schemata required to interpret them (Pinker, 1990; Padilla *et al.*, 2018). This underscores the pronounced context specificity of graph use in chemistry and the need to address graph competence in chemistry by fostering the development of flexible and transferable graph schemata.

The frequent use of chemistry-specific special forms also presents an opportunity: engaging with these representations may foster domain-specific ways of thinking and working (Shanahan *et al.*, 2011), while exposure to unfamiliar and atypical forms of visual representation may also help students develop the cognitive flexibility to adapt to new representational formats – a skill valuable not only in chemistry but across the sciences (Honra and Monterola, 2026). These findings also point to a research gap: further investigation is needed to better understand how students engage with these representations.

### SQ3: graphs across different content areas

Analyzing graphs in relation to the specific content areas in which they appear reveals that learners in chemistry must simultaneously learn *about* graphs (how to read, explain, and interpret them) and learn *with* graphs (how to use them as tools for understanding scientific processes and phenomena). This dual demand is particularly evident in chemistry, where graphs often depict already abstract subject matter in an additional abstract visual form. An example from our study further illustrates this point: in upper secondary education, graphs are the most frequently used type of visual representation in the content area "Reaction rates and chemical equilibrium" – a topic recognized as one of the most challenging topics both to learn and to teach (Hackling and Garnett, 1985; Bergquist and Heikkinen, 1990; Barke, 2006), underscoring the necessity of explicitly fostering graph competence.

The analysis also shows that graphs often appear in blended digital-analog hybrid contexts, with printed textbooks frequently including QR codes that link to digital graphs. This integration underscores that students increasingly need both graph competence and media literacy. The inclusion of digital graphs in chemistry textbooks aligns instructional materials with contemporary educational realities, preparing students to navigate 21st-century demands. Digital graphs offer unique opportunities compared with static printed ones, allowing real-time data collection and visualization during experiments, with graphs updating dynamically as data are recorded. An example is the use of sensors and data loggers in reaction rate experiments, where students can observe concentration changes of reactants or products over time with the corresponding graph displayed live on a digital device. Therefore, textbooks represent a transitional phase between traditional analog materials and emerging digital or open educational resources (Robinson *et al.*, 2014; Sansom *et al.*, 2021). In conclusion, the integration of analog and digital graph use in school contexts is still in its early stages. Further research is needed to explore this transition in depth and to support the parallel development of both graph competence and media literacy in contemporary chemistry education.

### SQ4: graph-related tasks, competence components and competence levels

The analysis reveals a progression regarding graph-related tasks: graph construction tasks are predominant in lower secondary education textbooks, whereas information extraction tasks dominate in upper secondary education textbooks. This suggests that lower secondary education textbooks primarily emphasize procedural skills related to graph construction, while upper secondary education textbooks focus on analyzing and interpreting pre-existing graphs, presumably building on foundational competencies acquired earlier.

Regarding cognitive complexity, descriptive engagement with graphs (level 2) plays a major role throughout lower secondary education textbooks. However, in upper secondary textbooks, tasks increasingly target greater cognitive complexity (levels 3–5), requiring advanced analytical skills and deeper subject-specific understanding (Ainsworth, 2006). This shift from description to more complex tasks, such as explanation, demonstrates how students encounter increasing variety and complexity in graph types and tasks as they advance.

It remains an open question whether students' graph competence actually develops in parallel with the increasing complexity of these tasks, whether students receive sufficient scaffolding to manage these more demanding tasks, or whether foundational skills from earlier stages are consistently reinforced. These considerations underscore the importance of investigating and, subsequently, fostering graph competence across the full range of cognitive demands and of providing tasks with graduated complexity early on, as such tasks are crucial for achieving comprehensive graph competence (Jahnke, 2020). This is particularly evident in middle school textbooks, where differentiation among graph tasks is less pronounced. Particular attention should be devoted to tasks requiring higher cognitive engagement, where students are required to explain and interpret graphs, as without deep engagement, "learners will only analyze graphs superficially [...] and do not fully understand their subject matter" (Jahnke, 2020, p. 383). Strengthening these abilities is thus crucial not only for promoting deeper understanding of chemical concepts represented in graphs but also for equipping students with the skills necessary to critically evaluate graphical data in everyday contexts such as advertising.

**Additional findings: integration of text and graphs.** Beyond SQ1–4, this study identified supplementary results regarding the integration of text and graphs in chemistry textbooks, as well as the use of colors in graphs. These insights complement the main discussion and address further parts of graph competence in chemistry education.

Prior research shows the importance of captions: well-designed captions play a crucial role in supporting students' understanding and facilitating accurate interpretation of visual representations, helping readers distinguish relevant details and understand their intended meaning (Bowen and Roth, 2002; Pozzer and Roth, 2003; Wu and Shah, 2004; Pozzer-Ardenghi and Roth, 2005; Kapıcı and Savaşçı-Açıkalın, 2015; Upahi and Ramnarain, 2019). Conversely, inadequate or missing captions may require students to rely on additional cognitive resources to encode the intended meaning, thus making comprehension more difficult or even hindering it (Pozzer-Ardenghi and Roth, 2005; Cheng and Gilbert, 2015). Our analysis reveals that approximately one-third of all visual representations in the analyzed chemistry textbooks are insufficiently supported by captions. Specifically, 27.59% of the graphs ($n$ = 128; $N_{\text{directly observable graphs}}$ = 464) and 32.04% of the realistic pictures ($n$ = 822; $N_{\text{directly observable realistic pictures}}$ = 2566) lack captions entirely. This finding is consistent with previous studies reporting missing (Kapıcı and Savaşçı-Açıkalın, 2015; Upahi and Ramnarain, 2019) or overly brief captions in textbooks (Schnotz, 2001; Bowen and Roth, 2002). Bowen and Roth (2002) contrast textbooks with scientific journals, where captions are extensive, often exceeding 100 to 200 words. In contrast, the analyzed chemistry textbooks generally lack such detailed guidance, providing only brief or absent captions that offer limited interpretive support. It is important that captions do more than merely describe the visual representation or restate the topic; they should support learners in interpreting the information presented. Since the textbooks analyzed here only partially meet these criteria, there is a clear need to improve the quality and function of captions to better support students' understanding of graphs in chemistry education.

A second notable finding concerns the lack of explicit references to graphs within the accompanying text, such as direct mentions or linking phrases. Research demonstrates that the accompanying text is a crucial resource for learners, as it supports the interpretation of visual representations (Pozzer-Ardenghi and Roth, 2005). When graphs are not explicitly referenced, explained, or interpreted in the text, they often appear out of context, forcing students to independently establish connections between the graph and the surrounding content. As a result, students may struggle to identify a graph's purpose, understand its relationship to the text, or comprehend it at all. This additional cognitive effort increases students' overall cognitive load, particularly because graphs are already abstract and demanding to interpret, and may ultimately hinder understanding.

These findings are consistent with prior research (Bowen and Roth, 2002; Kapıcı and Savaşcı-Açıkalın, 2015), which found that explanations or interpretations of graphs are often missing from high school textbooks, in contrast to the more detailed guidance typically provided in scientific articles. Establishing explicit links between text and graphs – through numbering or explicit references – helps to create coherence and facilitates comprehension (Pozzer-Ardenghi and Roth, 2005). Accordingly, textbook authors and teachers should systematically ensure the explicit integration of text and visual representations to support graph comprehension.

**Additional findings: use of color.** The analysis further revealed that color and color schemes are frequently used in textbooks to support students' understanding of graphs and the relationships they represent. Graphs containing multiple lines or curves often employ distinct colors for each, enabling students to differentiate between them more easily. Another design strategy involves the consistent use of color for specific words or technical terms appearing both in the graph and in the accompanying text, thereby facilitating cognitive connections (Pozzer-Ardenghi and Roth, 2005). Through such visual-textual consistency it is possible to establish explicit links between text and visual representations, supporting students' comprehension and cognitive processing (see previous section). A promising enhancement would be to extend this practice by displaying relevant text passages in the same colors as the corresponding lines or elements in multi-line graphs, making these connections even more transparent. Although this feature was not implemented in any of the textbooks analyzed, it represents a valuable direction for future textbook design. In summary, the deliberate use of color in textbook graphs can play a vital role in fostering graph competence by making relationships more salient, coherent, and easier to comprehend.

# Limitations

When interpreting the findings of this study, several factors should be considered that may affect their generalizability. One limitation concerns the textbook sample. Although we sought to include a broad selection of materials from multiple German publishers, the analysis represents only a subset of available instructional resources. Consequently, the use of graphs in other textbooks may differ from the patterns identified in this study. It also remains unclear whether the competence levels outlined in this study differ in actual cognitive demand, represent a developmental progression, or apply equally across various graph types.

Furthermore, one limitation of our coding approach is that mixed and special forms of graphs were excluded from the graph task coding (corresponding to SQ4). As a result, the competence required to extract information from these non-canonical visual representations is not reflected in our findings. Further research should therefore include such forms to more comprehensively capture the full scope of graph-related competence in chemistry education. Taken together, these limitations highlight the need for further studies to validate, refine, and extend the current findings.

# Implications

Building on the study's findings, this section outlines implications for (1) teaching graphs, (2) the design of instructional material, and (3) directions for future research.

### Implications for teaching graphs

To overcome graph-related learning difficulties and fully realize the educational potential of graphs, the development of graph competence must be an explicit focus of instruction, as "it is a learned skill, it doesn't just happen by itself" (Dreyfus and Eisenberg, 1990, p. 33; see also Angra and Gardner, 2017; Rodriguez *et al.*, 2019; Gardner *et al.*, 2024). Instruction should therefore not only support learning *with* graphs but also deliberately foster learning *about* graphs. This study demonstrates that, although graphs are prevalent across all content areas of chemistry textbooks, these resources typically provide only limited, and often implicit, guidance on how graphs should be read, described, explained, and interpreted. Moreover, textbooks offer little structured support for the systematic, long-term development of students' graph competence. Teachers therefore play a crucial role in explicitly guiding students in the effective and reflective use of graphs (Rodriguez *et al.*, 2019; Gardner *et al.*, 2024). To promote graph competence, students should regularly engage in hands-on scientific graph practices, which provide an authentic experience of scientific inquiry (Roth *et al.*, 1999). Constructing graphs in experimental contexts – such as titration experiments or solubility studies – enables students to directly connect observable phenomena with their graphical representations.

It is equally important that teachers use graph-related terminology consistently and in accordance with disciplinary norms, both verbally and in written materials, as students can only fully comprehend graphs when they are familiar with the subject-specific language conventions in which they are embedded. Such an approach is particularly important for students whose first language is not the language of instruction.

The analysis reveals that many graphs in chemistry are abstract in both form and content, often featuring elements that make them particularly challenging for students, such as unfamiliar graph forms, missing captions, or the use of arrows to indicate relationships. These features underscore the importance of teachers critically evaluating the textbooks they use, considering both their educational potential and possible barriers to student learning. Teachers can address these challenges by selecting representative textbook graphs as examples when introducing graph types and functions. Encouraging students to compare similarities and differences among these forms can help clarify representational conventions and foster deeper understanding of how and why scientific information is visualized in different ways. To further support learning, teachers should provide reading prompts or guiding questions that promote active engagement with visual representations and their connections to accompanying text (Angra and Gardner, 2017; Jian, 2021; Meyer and Pietzner, 2022; Stoczynski *et al.*, 2026). Without such scaffolding, students may be left to interpret graphs independently, increasing cognitive load (Kapıcı and Savaşcı-Açıkalın, 2015). As students' competence develops, instruction should gradually shift toward greater autonomy, encouraging learners to interpret graphs independently rather than reproducing a teacher's or textbook's interpretation.

Since textbooks often provide insufficient guidance, teachers' explanations become central for fostering graph competence. Effective explanations require both a solid understanding of graphs and their specific applications in chemistry (*subject matter perspective*), and an awareness of students' prior knowledge and common misconceptions regarding graphs (*audience perspective*; Osborne and Patterson, 2011; Fichtner and Groß, 2025). However, research shows that even prospective science teachers struggle with graph interpretation (Bowen and Roth, 2005), often making the same errors as middle school students (Von Kotzebue *et al.*, 2015). These persistent difficulties highlight the challenges teachers are likely to face when teaching about graphs and indicate the need for explicit preparation during teacher education (Von Kotzebue, 2014). Accordingly, prospective chemistry teachers should engage with authentic, chemistry-specific graphs early in their studies and develop pedagogical strategies for their effective use and explanation in instruction, reflecting the types of graphs commonly encountered in classrooms. Such training should follow established quality criteria for instructional explanations (Fichtner and Groß, 2025) and include opportunities to practice explaining complex or non-intuitive graphs, thereby strengthening both their subject-matter understanding and pedagogical repertoire.

### Implications for the design of instructional material

According to Doll *et al.* (2012), two parameters of teaching quality can be systematically influenced: teachers' professional competence and the quality of instructional materials, including textbooks. Moreover, students' graph competence is shaped not only by instruction but also by the visual characteristics of the graphs themselves. Both factors underscore the importance of providing students with high-quality materials that actively support the development of graph competence. To this end, textbook graphs should be carefully and deliberately selected and designed with clear didactic intent to ensure that textbooks effectively fulfill their educational role (Bowen and Roth, 2002; Rusek and Vojíř, 2019).

Within the graphs themselves, grid lines can enhance the readability of data points, color-coding can draw attention to critical sections or values, and labels can highlight key features (Schnotz, 2001). Graphs should always be accompanied by captions that are both meaningful and pedagogically purposeful, directing learners' attention to the central concept or message conveyed (Schnotz, 2001; Bowen and Roth, 2002; Pozzer and Roth, 2003; Kapıcı and Savaşcı-Açıkalın, 2015). Additional explanatory elements may also be placed near the graph, within the surrounding text, as embedded symbols, or through digital features such as interactive animations or short videos, to guide interpretation and provide an explicit conceptual framework. Moreover, graphs and their corresponding text should be explicitly connected through indexical or textual references (Pozzer and Roth, 2003; Kapıcı and Savaşcı-Açıkalın, 2015; Upahi and Ramnarain, 2019) and positioned in close proximity to one another (Pozzer and Roth, 2003). Taken together, these design principles highlight that well-crafted textbook visual frameworks, integrating textual, graphical, and multimedia elements, can significantly enhance students' comprehension and promote the systematic development of graph competence in chemistry education.

### Implications for future research

Based on the present findings, several promising directions for future research emerge. One important avenue concerns the instructional functions of graphs and realistic pictures in chemistry textbooks, particularly in relation to their integration with text. While existing frameworks classify visual elements in general (*e.g.*, Carney and Levin, 2002, for pictures; Pozzer and Roth, 2003, for photographs), subject-specific applications in chemistry remain limited and warrant further investigation. Our analysis suggests a preliminary categorization: some graphs concretize and supplement textual explanations by providing precise quantitative information (*e.g.*, concentration values at specific reaction time points), whereas others serve as independent learning objects that introduce new information not explicitly addressed in the accompanying text, such as energy profiles visually conveying activation energy. Future research could examine the distribution and instructional functions of such graphs across different chemistry textbooks and grade levels.

A second line of inquiry involves the comparative analysis of static and dynamic graphs in textbooks. Prior research consistently demonstrates that learners process static and dynamic visual representations differently (*e.g.*, Ainsworth, 2006; Höffler *et al.*, 2013). With the increasing integration of digital technologies, including QR-linked interactive resources and real-time data displays, dynamic graphs such as plots from experiments are becoming more accessible in educational contexts. Systematic studies are therefore needed to determine how these representations are incorporated into chemistry textbooks and digital material, and how they influence students' comprehension and engagement.

Another promising research direction concerns the role of captions in supporting graph interpretation. Future studies could explore the quality, frequency, and pedagogical function of captions in chemistry textbooks. Qualitative analyses might investigate whether captions primarily serve descriptive or explanatory purposes (*e.g.*, Pozzer and Roth, 2003; Pozzer-Ardenghi and Roth, 2005; Upahi and Ramnarain, 2019), while quantitative studies could trace how the proportion of explanatory captions changes across educational levels. Such work would deepen our understanding of how captions mediate between textual and visual information and how their pedagogical value evolves with increasing complexity.

Further research could also adopt a meta level comparative perspective. For example, data from university level textbooks and scientific journal articles could be compared with school level materials to identify differences in use, density, and instructional functions of visual representations. Bowen and

Roth (2002), for instance, found that high school ecology textbooks contained the fewest visual representations – on average, 1.38 per page – compared to other educational media. Whether similar patterns apply to chemistry, and disciplinary context shapes the quantity and role of visual representations, remains an open question. Similarly, comparing traditional print textbooks, digital textbooks, and open educational resources could reveal how format influences the integration and educational effectiveness of graphs (Robinson *et al.*, 2014; Sansom *et al.*, 2021; Meyer and Pietzner, 2022).

In this study, we focused specifically on the graph competence component "Information extraction." Future research could examine graph construction in greater depth, thereby contributing to a more comprehensive understanding of graph competence in chemistry education. In addition, the graph-related tasks found in textbooks provide further opportunities for investigation, as the textbook-based analysis could be extended to explore whether the levels of cognitive complexity addressed by tasks correspond to students' actual performance. Complementary classroom-based research would also be valuable. Incorporating teachers' perspectives could better reflect authentic instructional contexts, as "design principles will not have much meaning unless they are studied in the context of the classroom" (Cook, 2011, p. 183). Such research could investigate how teachers integrate textbook graphs into chemistry instruction, and whether classroom practices place greater emphasis on information extraction or graph construction.

More detailed insights into the specific challenges that students face when interpreting or constructing graphs and solving graph-based tasks of varying complexity in chemistry are especially needed. Therefore, we concur with Leinhardt *et al.* (1990, p. 54), who stated, "we need to understand what students know." Further studies should identify and evaluate targeted instructional strategies that address these challenges and sustainably foster the development of students' graph competence.

Finally, the results of this study underscore the need for continued research to clarify how graphs function as domain-specific tools in chemistry and to determine effective ways of supporting the development of graph competence. Future investigations should explore which teaching strategies, task designs, and textbook approaches best support students in learning with and learning about graphs, and how such approaches can be adapted to different learner profiles and content areas. Ultimately, advancing research in this area will contribute to a deeper understanding of graphs as central mediators of meaning in chemistry education and to preparing students for critical engagement with graphical information in an increasingly data-driven world.

## Conflicts of interest

There are no conflicts to declare.

## Data availability

The data that support the findings of this study are available from the corresponding authors upon reasonable request.

## Appendix

Tables 10–12.

Table 10 Category scheme underlying the analysis

| Number | Page | Figure | Caption | Visual representation type | Visual representation subtype | Content area | Text/task assignment | Competence component (level) | Other |
|---|---|---|---|---|---|---|---|---|---|
| Listing/ numbering of the visual representation | Page number of the visual representation | Photo of the visual representation | Caption text accompanying the visual representation | Category of the visual representation | Subtype of the visual representation | Assignment to content area | Assignment to text, task, or both; in the case of tasks, notation of task text | Assignment to competence component and, if applicable, competence level | Additional comments or observations |

Table 11 Graphs per 100 pages and distribution of visual representation types across analyzed chemistry textbooks (absolute numbers and percentages). Percentages indicate the proportion of each representation type relative to the total number of visual representations in each book

| Publisher | School type and educational level | Graphs per 100 pages | Graphs | Realistic pictures | Mixed forms |
|---|---|---|---|---|---|
| Klett | Lower secondary education (grammar school) | 10.38 | 49 (10.25%) | 413 (86.40%) | 16 (3.35%) |
| | Lower secondary education (middle school) | 8.31 | 34 (4.76%) | 672 (94.12%) | 8 (1.12%) |
| | Upper secondary education (grammar school) | 23.57 | 124 (29.38%) | 288 (68.25%) | 10 (2.37%) |
| C.C.Buchner | Lower secondary education (grammar school) | 15.63 | 70 (20.83%) | 262 (77.98%) | 4 (1.19%) |
| | Upper secondary education (grammar school) | 17.29 | 130 (30.95%) | 271 (64.52%) | 19 (4.52%) |
| Westermann | Lower secondary education (grammar school) | 22.19 | 75 (17.56%) | 348 (81.50%) | 4 (0.94%) |
| | Lower secondary education (middle school) | 7.41 | 32 (8.96%) | 317 (88.80%) | 8 (2.24%) |
| | Upper secondary education (grammar school) | 34.05 | 158 (39.90%) | 227 (57.32%) | 11 (2.78%) |

Table 12 Distribution of graph types (absolute numbers and percentages) in chemistry textbooks (line graphs, column charts, bar graphs, scatter plots, pie charts, scales, special forms, and unassignable forms). Percentages indicate the proportion of each graph type relative to the total number of graph types within each school type

| | Line graph | Column chart | Bar graph | Scatter plot | Pie chart | Scale | Special form | Unassignable | Total |
|---|---|---|---|---|---|---|---|---|---|
| Lower secondary education (grammar school) | 86 (44.33%) | 20 (10.31%) | 16 (8.25%) | 9 (4.64%) | 10 (5.15%) | 13 (6.70%) | 40 (20.62%) | 0 (0%) | 194 |
| Lower secondary education (middle school) | 28 (42.42%) | 8 (12.12%) | 8 (12.12%) | 2 (3.03%) | 13 (19.70%) | 4 (6.06%) | 2 (3.03%) | 1 (1.52%) | 66 |
| Upper secondary education (grammar school) | 277 (67.23%) | 11 (2.67%) | 6 (1.46%) | 1 (0.24%) | 10 (2.43%) | 24 (5.83%) | 82 (19.90%) | 1 (0.24%) | 412 |
| Total | 391 | 39 | 30 | 12 | 33 | 41 | 124 | 2 | 672 |

**List of analyzed textbooks**

Bohrmann-Linde C. and Siehr I. (ed.), (2022), *Chemie Einführungsphase*, C.C.Buchner.

Bohrmann-Linde C. and Siehr I. (ed.), (2023), *Chemie Qualifikationsphase*, C.C.Buchner.

Bohrmann-Linde C., Kröger S. and Siehr I. (ed.), (2020), *Chemie Gesamtband Sekundarstufe I.*, C.C.Buchner.

Fink S., Graf E., Günkel T., Himmler U. and Münzinger W., (2023), *Blickpunkt Chemie 7-10*, Westermann.

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Gietz P., Kasprzak T., Knetsch R., Peppmeier R., Schäpers B. and Weizel B., (2012), *Prisma Chemie $\frac{1}{2}$*, Ernst Klett Verlag.

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Menze S., van Nek R., Schulte-Coerne R. and Sieve B. (ed.), (2023), *Chemie heute SII*, Westermann.

Van Nek R. and Ratermann M. (ed.), (2021), *Chemie heute*, Westermann.

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