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Critical Thinking through Three Levels of Representation: An Analysis of Carbohydrate Concepts in Chemistry Textbooks

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Abstract

For a student to gain a deeper understanding of concepts in chemistry, they need to learn concepts at three levels of representation: macroscopic, submicroscopic, and symbolic. The three levels of representation of information are crucial for developing critical thinking skills. But the textbook, which is the main learning resource, plays a vital role in helping a student relate concepts at the three levels. The objective of this research was to assess the display of carbohydrate representation at three levels in ten general chemistry textbooks. In order to examine 120 visual representations, this research employed qualitative content analysis, with five criteria developed from the work of Gkitzia et al. (2020). Criteria C1-C5 include the following: type of representation (C1), interpretation of surface characteristics (C2), relationship to text (C4), presence and nature of captions (C5), and level of correlation between elements that comprise the different representations. Thirdly, the usefulness of the proposed criteria was compared to chemistry textbooks. The results showed that there was a dominance of representations at the symbolic level. Moreover, some of the representations were found to have insufficient subtitles to give meaning, especially at the submicroscopic level. The conceptual understanding of students can be impaired by the dominance of symbolic representations and the absence of visual support for other levels. To ensure that critical thinking is done effectively, this study stresses the need to develop learning materials that incorporate the three levels of representation in a balanced manner. These five criteria can also be used to analyze existing school textbooks and to design new Chemistry textbooks.

Keywords: Three Levels of Representation, Content Analysis, Carbohydrates

INTRODUCTION

Chemistry studies phenomena that cannot be directly experienced, such as molecular structure and the interactions between atoms, molecules, and ions, which are invisible and untouchable to the human senses. To represent these phenomena, scientists use several types of chemical representations (Mathewson, 2005; Rahhou et al., 2015; Gkitzia et al., 2020). Each chemical phenomenon consists of three parts. The macroscopic part reveals what is observable, the submicroscopic part reveals what occurs at the molecular level, and the symbolic part reveals how the phenomenon is represented (Johnstone, 2000; Mansouri, 2007).

Macroscopic representations are tangible, observable, and measurable objects, both in the chemistry laboratory and in everyday life (Treagust et al., 2003; Carney & Levin, 2002). Video tapes or pictures, whether photographs or drawings, of chemical events can illustrate this. Submicroscopic images reveal macroscopic events such as atoms, ions, and molecules that cannot be viewed with the naked eye or even with a microscope. The most popular systems used in this representation are molecular models, with the most common being sphere-and-rod, rod-and-rod, and space-filling (Wu & Shah, 2004; Gkitzia et al., 2020). Symbolic is a submicroscopic representation used to describe atoms, whether consisting of one element, or included in a group of several elements, or symbols to describe electric current or flow, punctuation marks under the line to indicate the number of atoms in an ion or molecule, and letters to indicate the physical form of a substance and ionic equations in chemistry (Rahhou et al., 2015; Johnstone, 2000). Three-dimensional symbolic representations include Lewis structures, graphs, algebraic equations, chemical symbols, chemical equations, reaction mechanisms, Newman and Fischer projections, and more (Kozma et al., 2000).

The role of macroscopic, submicroscopic, and symbolic representations is crucial in chemistry learning, as they help students develop conceptual understanding (Chittleborough, 2014; Lansangan et al., 2018). Therefore, chemical representation is very important for various educational materials, such as school textbooks, educational multimedia software, slides, video displays, computer animations, molecular models, and so on.

Although different levels of representation—macroscopic, submicroscopic, and symbolic—play a crucial role in building students' conceptual understanding, research consistently shows that students still face difficulties in comprehensively understanding and connecting these three levels (Talanquer, 2022; Nyachwaya & Wood, 2014; Eilks et al., 2007; Tan et al., 2009). In practice, in the classroom, macroscopic, submicroscopic, and symbolic representations have been used, but they do not address the relationship among the three. (Chuenmanee & Thathong, 2018).

Conceptual understanding is an important aspect that needs improvement in the learning process, as it serves as a benchmark for assessing students' mastery of the material (Sastrika et al., 2013) . Students' understanding of carbohydrates still faces significant conceptual challenges. Students often struggle to interpret "simple" representations that actually require high visual and conceptual competencies. For example, the structure of glucose and the formation of glycosidic bonds are difficult to understand because they require high visual and conceptual competencies (Derman, 2023).

Critical thinking is one of the thinking skills students must master in this century, alongside three others: creativity, communication, and collaboration (National Education Association, 2019). This is because companies set job requirements for job seekers, namely critical thinking and problem-solving skills, rather than just science competencies (Kyllonen, 2012). Because multiple problem perspectives are involved in critical thinking, explicitly integrating creative problem-solving into the learning process is crucial for improving students' critical thinking (Dekker, 2020).

Learning chemistry can be challenging for a variety of reasons, ranging from students' backgrounds to the science's abstract nature. Educators need to recognize the importance of using multiple levels of representation in learning resources to help students better understand chemistry. Textbooks are essential learning tools because they are widely available and easily accessible to both students and teachers (Upahi & Ramnarain, 2019).

For textbook representations to be effective, they must help students understand relevant chemical concepts. The meaning of the visual features of the representations must be clearly explained to students. Essentially, a representation is useless if students cannot correctly grasp its intended meaning. The direct connection between the representation and the corresponding textual content is also very significant. In cases where captions are used, they must be clear and explain the representation in detail (Gkitzia et al., 2020). The different terminologies that researchers apply to define different levels of representation can also lead to confusion. In cases where the terms are supposed to be equivalent all through the chemical triplet, this problem is very serious (Talanquer, 2022).

As previously mentioned, chemical representation is a very important element of teaching materials such as textbooks and modules. However, chemical representation alone is not enough to improve students' understanding. Moreover, misunderstandings can be caused by chemical representation that does not follow certain standards.

In this context, the aim of this study is to conduct an in-depth analysis of the representation of carbohydrates in chemistry textbooks. This research will evaluate the representation of the three levels of representation (symbolic, submicroscopic, and macroscopic) in textbooks. The findings of this analysis are expected to provide insight into the potential of textbooks to support or hinder efforts to foster students' critical thinking in chemistry.

METHOD

Research Method

For the study of a particular phenomenon, the research design used in this study was qualitative (Creswell, 2002), specifically the representation of the definition of carbohydrates in chemistry textbooks. The methodology used for this study included qualitative content analysis of ten general chemistry textbooks. Qualitative content analysis is a research method used for the organization of communication content, both manifest and latent. This research method involves a series of actions that are unique to the research situation. The primary tool used to systematize the desired content is a category system. In the most general definition of the term "text," all forms of text are objects of analysis (Stamann et al., 2016). This approach was considered appropriate for the study of the representation of carbohydrates in textbooks for the effective understanding of chemical concepts.

Data Source

The primary data source for this study was a specific chapter devoted to the topic of carbohydrates from general chemistry textbooks titled; General chemistry principles and modern applications 10th Edition (Petrucci et., 2011), Chemistry: The Molecular Nature of Matter and Change 6th Edition (Jespersen et al., 2012), Chemistry: The Molecular Nature of Matter and Change 9th Edition (Silberberg & Amateis, 2006), Chemistry: The Central Science 12th Edition, Organic Chemistry 4th Edition, Organic Chemistry 6th Edition, Organic Chemistry 9th Edition (McMurry, 2016), Chemistry 7th Edition (Zumdahl & Zumdahl, 2010), Chemistry 10th Edition (Whitten et al., 2014), Chemistry: The Central Science 15th Global Edition (Brown et al., 2022). These textbooks were selected because they are commonly used in basic chemistry courses at the university level.

Research Procedure

The research procedure was conducted through several systematic stages:

1) Identification and documentation: all visual representations within the selected chapterwere identified. These representations included diagrams, illustrations, photographs of experiments, graphs, and tables. Each identified representation was then digitally documented (via screenshot) and assigned a unique code (e.g., Fig-01, Fig-02) for tracking purposes.
2) Data analysis: data analysis was performed by adapting the framework for evaluating chemical representations developed by Gkitzia, Salta, and Tzougraki. Each documented representation was analyzed using five main criteria:
   a. C1 - type of representation: to categorize each image into macroscopic, submicroscopic, symbolic, multiple, hybrid, or mixed types.
   b. C2 - interpretation of surface features: to evaluate whether the meaning of visual elements (such as colors, shapes, or labels) was explained explicitly, implicitly, or was ambiguous.
   c. C3 - relatedness to text: to examine the level of coherence between the representation and the surrounding text, as well as the implicit references from the text to the image. The criteria are: related and connected, related and unconnected, related and connected, related and unconnected, related and unconnected, or unrelated.
   d. C4 - existence and properties of a caption: to assess the presence and appropriateness of a caption in providing context and clarity to the image. The criteria include the

existence of an appropriate caption, the existence of a problematic caption, or the absence of a caption.

e. C5 - degree of correlation between components: specifically for multiple representations, to analyze the presence of visual cues (such as arrows or lines) that connect components from different representational levels. The level of linkage is sufficiently linked, insufficiently linked, or unlinked.

3) The whole process of analysis and coding was recorded in a coding sheet to ensure consistency and reliability of the data.

RESULTS AND DISCUSSION

The purpose of this study is to evaluate how chemical bonds are portrayed in a few books about chemistry. An instrument developed by Gkitzia, Salta, and Tzougraki is used to evaluate this chemistry book (Gkitzia et al., 2020). Type or level of representation (C1), interpretation of the representation (C2), relationship with text (C3), representation and description (C4), and degree of agreement between representations gathered from various sources (C5) are the criteria of the basic representation analysis instrument. As Table 1 illustrates, each criterion is composed of several categories.

Table 1. Criteria for the Evaluation of Chemical Representations and Their Characteristics

Criterion	Typology for Each Criterion
C1: Type of representation	Macro Submicro Symbolic Multiple Hybrid Mixed
C2: Interpretation of surface features	Explicit Implicit Ambiguous
C3: Relatedness to text	Completely related and linked Completely related and unlinked Partially related and linked Partially related and unlinked Unrelated
C4: Existence and properties of a caption	Existence of appropriate caption (explicit, brief, comprehensive, providing autonomy) Existence of a problematic caption No caption
C5: Degree of correlation between representations comprising a multiple one	Sufficiently linked Insufficiently linked Unlinked

An analysis of 120 visual representations from ten general chemistry textbooks, which are: General chemistry principles and modern applications 10th Edition (Petrucci et al., 2011), Chemistry: The Molecular Nature of Matter and Change 6th Edition (Jespersen et al., 2012), Chemistry: The Molecular Nature of Matter and Change 9th Edition (Silberberg & Amateis, 2006), Chemistry: The Central Science 12th Edition, Organic Chemistry 4th Edition, Organic Chemistry 6th Edition, Organic Chemistry 9th Edition (McMurry, 2016), Chemistry 7th Edition (Zumdahl & Zumdahl, 2010), Chemistry 10th Edition (Whitten et al., 2014), Chemistry: The Central Science 15th Global Edition (Brown et al., 2022), revealed a strong dominance of symbolic representations.

1st Criterion (C1): Type of Representation

The typology of criteria C1 comprises macro, sub micro, symbolic, multiple, hybrid, and mixed. Representations are classified in chemical phenomena that contain two or three levels of representation.

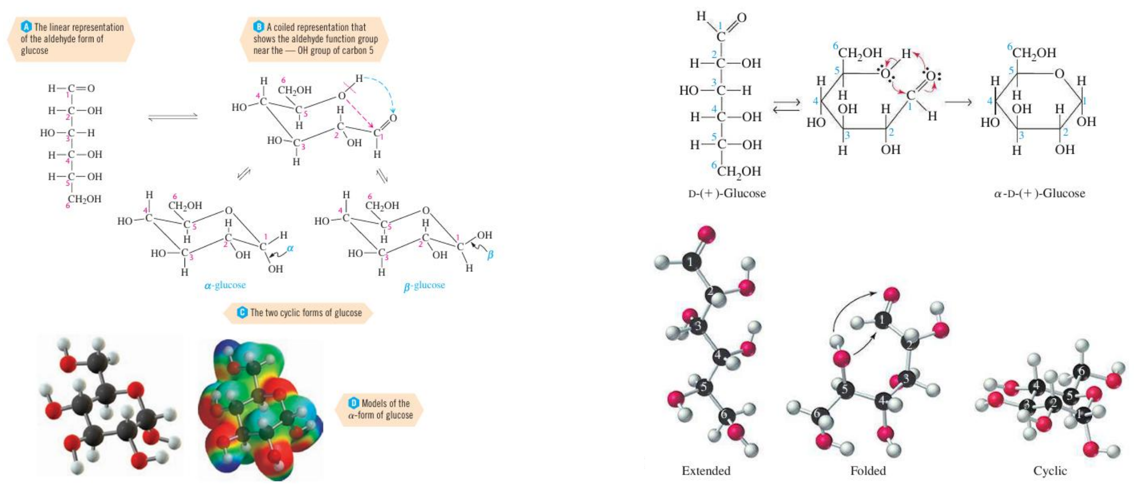

Figure 1. Example of Multiple Representations of Molecular Shapes

Figure 1 is a dual representation at the macro and sub micro levels, because it shows both submicroscopic and symbolic forms of molecules. Thus, Figure 1 consists of two representations—submicroscopic and symbolic—where the molecule's symbolic shape is clarified by its submicroscopic shape. The distinction between dual and hybrid representations is that dual representations focus on phenomena at two or three levels by merging two or three representations. On the other hand, hybrid representations merge the features of two or three levels into a single representation. A representation is considered to be hybrid if it merges the characteristics from one kind of chemistry (macro, sub micro, or symbolic) with the characteristics from another kind of representation.

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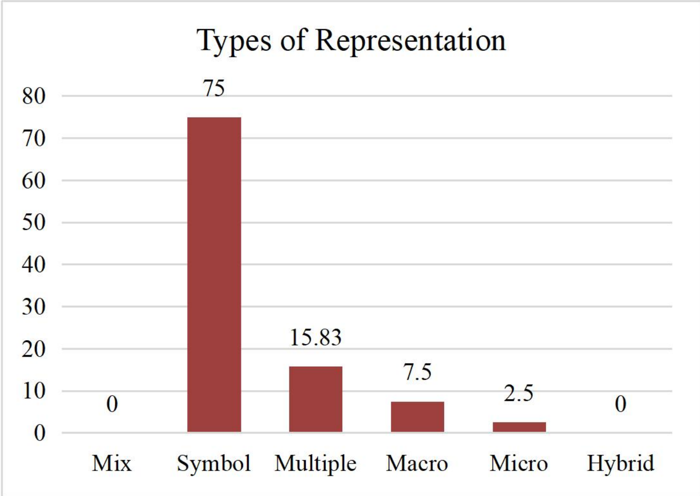

Figure 2. A Graphical Distribution of the Types of Representations in the Chemistry Textbooks

Figure 2 shows that the most frequently occurring representations in the textbooks were symbolic (75%), which included molecular structures, equations, formulas, and chemical tables. Next came dual representations (15.83%), followed by macroscopic (7.5%), and submicroscopic (2.5%). There was no evidence of hybrid and mixed representations in any of the textbooks.

2nd Criterion (C2): Interpretation of Surface Features

The second criterion involves the extent to which a representation is created and, more specifically, the extent to which a representation's surface features are labeled with clear information. The following typologies are examined and may be employed to classify representations: i) ambiguous (see Figure 3), ii) explicit (see Figure 4), or iii) ambiguous (see Figure 5). If all the features of the world are explained clearly, a representation is demonstrated as an implication.

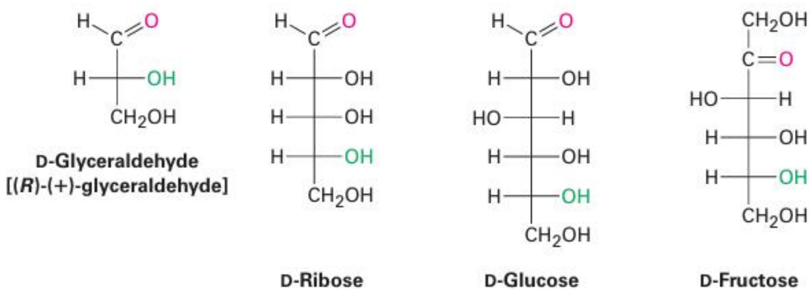

Figure 3. Examples of Explicit

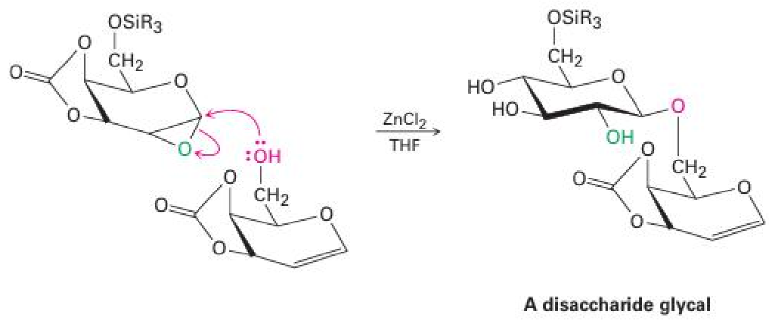

Figure 4. Example of Implicit

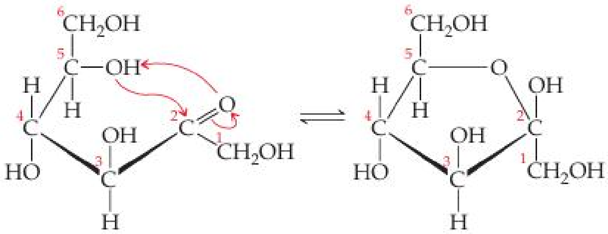

Figure 5. Example of Ambiguous Symbolic

Figure 3 is an example of explicit symbolic representation, because the shape characteristics of each compound are clearly labeled via internal captions. Figure 4 shows an implicit submicroscopic representation where it is stated, through internal information, that the compound formed after the reaction is a disaccharide glycal. At the same time, the reaction that occurred and the name of the compound before the reaction occurred are not clearly stated, although arrows are given in different colors. Figure 5 is an ambiguous submicroscopic example because it does not state the meaning of each surface feature.

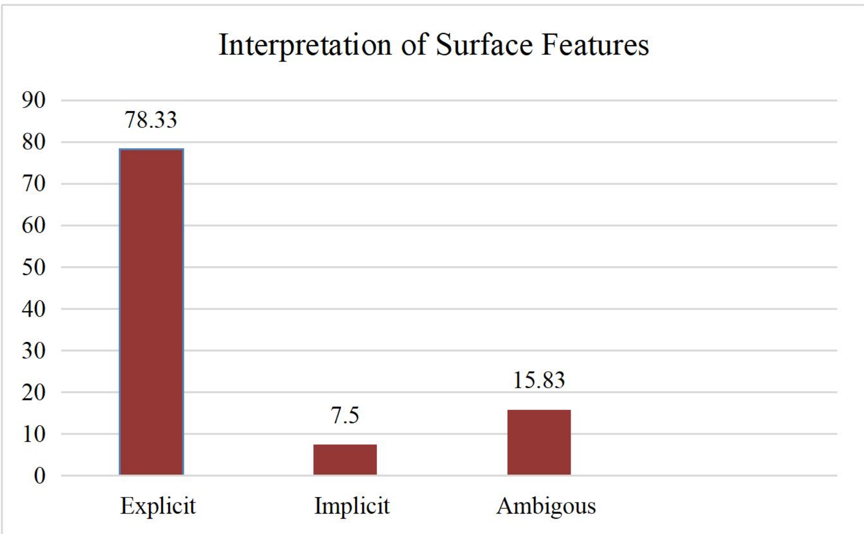

Figure 6. A Distribution of Interpretations of Surface Features

Based on the analysis of the criteria above, it is clear which criteria dominate in the carbohydrate materials chemistry book. Figure 6 shows that most representations are presented with explicit or clear features (78.33%).

3rd Criterion (C3): Relatedness to Text

This criterion assesses the level of coherence of the representation and its relationship to the text content, as well as whether there is a direct relationship between the representation and the text. The types of representation can be categorized based on the following classification: first, fully related and connected; second, fully related and unconnected; third, partially related and connected; and fourth, unrelated. As shown in Figure 7, a representation is said to be connected or unconnected if it represents the exact content of the text, partially related if it represents a known subject to the text but not exactly, or unrelated if it is not related.

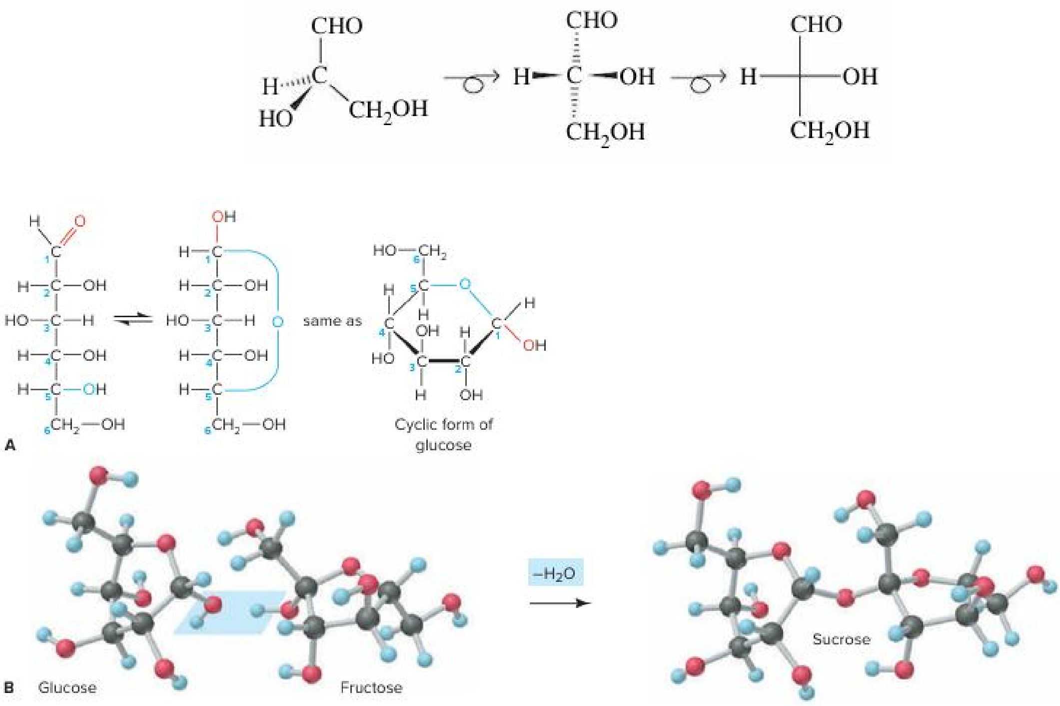

Figure 7. Examples of Symbolic, Completely Related and Linked, and Multiple Representations

In this study, chemistry representations showed that students had difficulty connecting equivalent concepts because they only saw letters, objects, and symbols, not the underlying concepts. Furthermore, research on textbook illustrations showed that students tended to look at images without paying attention to the necessary information (Sung & Mayer, 2012). Furthermore, Figure 6 shows the relationship between textbook representations and text content. Most images are also fully related and connected to the surrounding narrative text (80%).

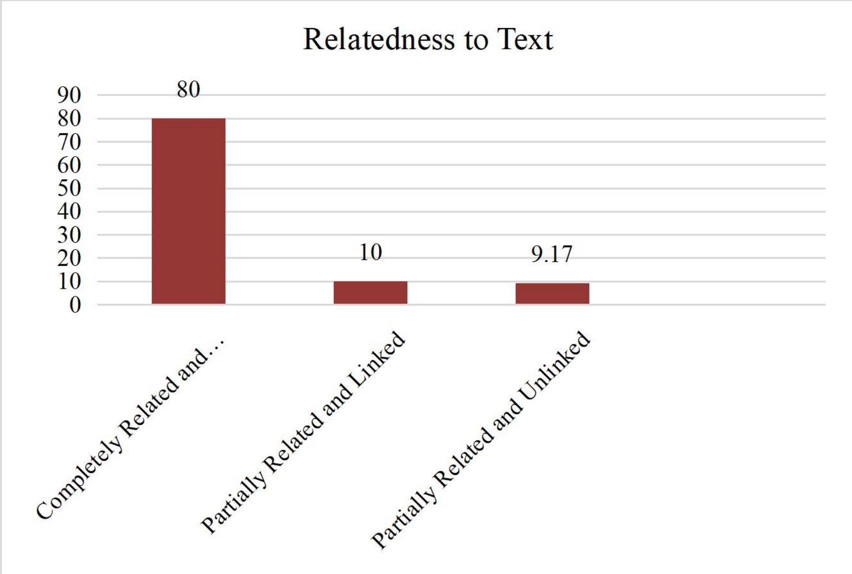

Figure 6. A Distribution of Chemical Representations that Are Related to Texts

4th Criterion (C4): Existence and Properties of A Caption

Appropriate captions should be clear, concise, and comprehensive, granting autonomy to the representation, and complying with these requirements. Representations are important because they can clarify the content and message (Gudyanga, 2024). In the analyzed book, almost all of the information lacks captions, as shown in Figure 8.

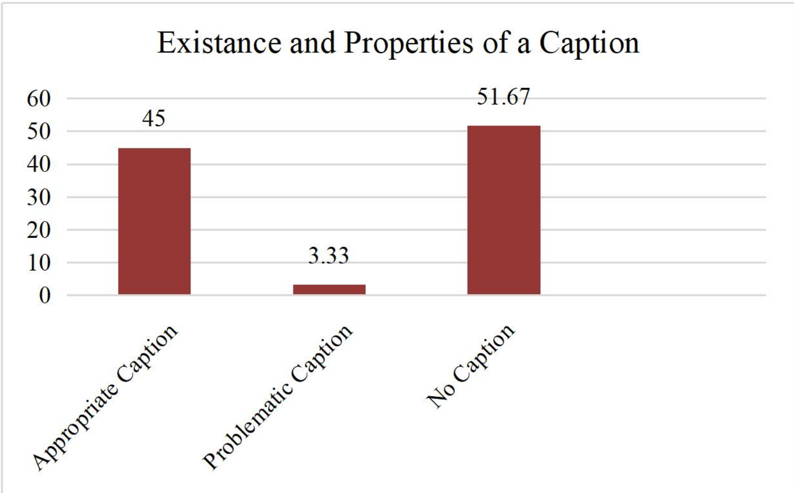

Figure 8. A Distribution of the Properties of Captions to Chemical Representations

Figure 8 shows the quality of the text accompanying the visual representations. As illustrated in Figure 8, less than half (45%) had captions that were deemed appropriate. Analysis of the text quality revealed significant problems in providing a self-contained context for the images. It was found that more than half of the visual representations (51.67%) were presented without any captions at all. This high percentage strongly correlates with previous findings on the dominance of symbolic representations. The majority of these symbolic representations were chemical equations presented as part of a text flow, numbered but lacking descriptive text.

5th Criterion (C5): Degree of Correlation Between the Components (Subordinate Representations) Comprising A Multiple Representation

The fifth criterion, which applies only to representations identified by the first criterion, analyzes how clear the correlation is between the surface features of different "subordinate" representations, each of which consists of several representations. These representations can be classified using the following classification: moderately connected, poorly connected, or unconnected.

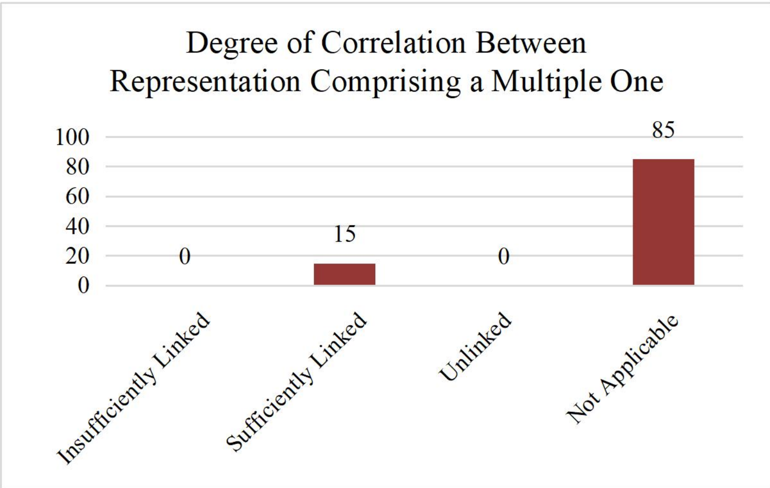

Figure 9. A Distribution of Correlation Between the Components Comprising a Multiple Representation

Figure 9 shows the quality of the visual relationships between components in several representations. Of the 120 images, 15% were classified as sufficiently connected, meaning that the relationships between levels of representation were clearly indicated using arrows or zoom lines. This finding suggests that when textbooks present multiple levels of representation in a single image, they generally clarify the visual relationships.

The high percentage in the not applicable category (85%) is not an anomaly, but rather a reflection of the distribution of representation types in the data. According to the methodology of Gkitzia et al. (2020), the C5 criterion applies only to images with multiple types. Only 15.83% of the images in this study were of more than one category. Most of the remaining images were identified as not appropriate since they were not methodologically analyzed with C5. Therefore, this finding confirms the previous finding that only a small percentage of all images are used to show many levels at once.

This study examines the representation of the concept of carbohydrates by eleven chemistry textbooks. The extent to which these images help students develop a conceptual understanding of chemical phenomena was the central aim.

The results indicate a strong dominance of symbolic representations. Reaction equations, formulas, symbols, and mathematical derivatives are some of the ways in which chemistry is usually dominated by symbolic aspects in textbooks. The dominance indicates an educational opportunity that has been missed. It may be difficult for students to understand the reasoning behind the reaction if there is no apparent connection between symbolic thoughts and reality in particles. Moreover, chemistry becomes abstract and not related to reality because it is not connected to reality, which eventually affects motivation.

The dominance of symbolic representations is a serious concern because it makes it even harder for pupils to understand chemical processes from different perspectives. They are at risk of suffering from cognitive overload and disinterest in learning as a result of their failure to gain fundamental conceptual understandings required for key chemistry concepts. This is supported by the views of Nyachwaya & Wood (2014), who argued that students find it harder to understand concepts when symbolic representations dominate textbook representations. In a bid to open up different views on the nature of chemistry, other forms of representation need to be introduced into chemistry learning as part of the efforts to reform learning.

Most of the representations used in the textbooks considered for this study included explicit surface features. This shows that the readers were not left bewildered by the meaning of the visual parts of the representation; for example, the labels on a graph and the key in a particle diagram were given in a clear manner. This makes it easy for students to understand the meaning of an image.

However, there were also important results regarding carbohydrate learning, which showed that some representations in textbooks and learning media are still implicit and ambiguous. This is a situation that requires students to interpret the meaning of the visual elements shown independently. For instance, in Fischer and Haworth projection images, the –OH, –H, and chiral carbon atoms are not always clearly labeled, making it hard for students to identify the D- or L-configuration and the relationship between linear and cyclic structures. This is also consistent with Roncevic's results that most students are unable to establish the relationship between basic concepts such as glycosidic bonds and polysaccharide synthesis because of poor visual representation in biochemistry learning (Roncevic et al., 2023). Moreover, the representation of glycan and carbohydrate structures in scientific settings is often inconsistent, which can worsen students' conceptual misunderstandings of the relationship between structure and function. This means that the ambiguity in representation can cause a variety of misunderstandings, including problems in distinguishing between open and cyclic structures, identifying the position of the anomeric group (α or β), or understanding the color and shape of atoms as chemical properties that are actually irrelevant (Daponte et al., 2021).

Most of these representations are closely linked to the text and complement each other in the dissemination of information. In general, these results indicate that when visual components are added, the textbooks are able to integrate them well into the story of learning, helping to explain the concepts being presented. However, for these representations to be more meaningful, they need to be accompanied by explanations that help students to construct meaning from the concepts. It is generally assumed that the meaning of the image is self-explanatory, but for most students, this is the first time they are interacting with such a visual form. Without proper explanatory support, the images in question have the potential to confuse and provide opportunities for misconstruction. Visual representations, therefore, are not only a complement to the text but also an important tool in helping students to construct meaning from scientific concepts (Fernandes Goes., 2020).

CONCLUSION

The results of the analysis show that most of the textbooks contain chemical representations that emphasize the symbolic level, which is mainly chemical reaction equations with labels, and are related to each other. However, some textbooks contain representations that are partially related and related categories. Based on the three chemistry textbooks, very few contain dual, hybrid, or mixed representations. Moreover, the information on chemical representations is very clear and specific, but some are accompanied by problems or lack explanations.

Chemical representations, whether macroscopic, submicroscopic, or symbolic, are essential components of textbooks and play a vital role in assisting students in understanding different concepts in chemistry, as well as helping teachers in their teaching endeavors. The third-level integration is essential for students to develop a comprehensive and meaningful understanding of different chemical concepts, such as carbohydrates. Thus, teachers must be informed of the limitations of textbook representations and should make efforts to complement them with more exploratory visual resources, especially those that represent chemical processes at the particle level. For instructional designers, the above findings can form a basis for creating teaching materials that have more integrated representations and informative captions, so that each visual contributes to students' conceptual learning.

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