JOURNAL OF CHEMICAL EDUCATION

Article

Cite This: J. Chem. Educ. 2018, 95, 347−354

pubs.acs.org/jchemeduc

Making Sense of Phenomena from Sequential Images versus Illustrated Text

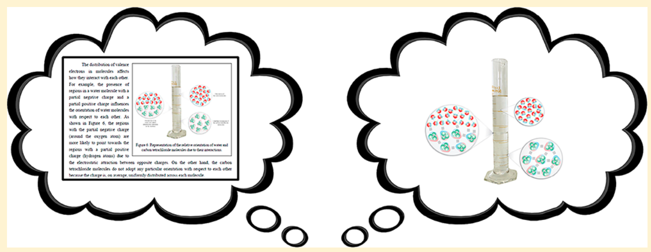
Karina C. Scalco,*,† Vicente Talanquer,‡ Keila B. Kiill,† and Marcia R. Cordeiro†

†Instituto de Química, Universidade Federal de Alfenas, 37130-000 Alfenas, Minas Gerais, Brazil

‡Department of Chemistry and Biochemistry, University of Arizona, Tucson, 85721 Arizona, United States

S *Supporting Information*

ABSTRACT: We present the results of a qualitative research study designed to explore differences in the types of reasoning triggered by information presented to chemistry students in two different formats. One group of students was asked to analyze a sequence of images designed to represent critical elements in the explanation of a target phenomenon. Another group of students was asked to analyze an illustrated text that introduced core concepts and ideas needed to understand the same phenomenon. Our study revealed major differences but also important similarities in student reasoning under the two conditions. Analyses of images led to more descriptive and limited accounts of the phenomenon than the analyses of text. However, these latter analyses often were plagued by conceptual confusions. Mechanistic explanations built under the two conditions frequently invoked a single causal factor as responsible for the phenomenon. Probabilistic effects were consistently neglected in these explanations.



KEYWORDS: *High School/Introductory Chemistry, First Year Undergraduate/General, Chemical Education Research, Multimedia-Based Learning*

FEATURE: Chemical Education Research

■ INTRODUCTION

The use of external visual representation of chemical entities (e.g., atoms, molecules, ions) and phenomena (e.g., chemical reactions, electron transfer) has become pervasive in educational materials, from textbooks to video clips to instructors' slides in chemistry courses.[1,2] Consequently, a significant amount of research has been conducted to characterize the nature of such representations and their impact on teaching and learning in the discipline.[1−4] Results from these and other investigations in science education[5,6] indicate that although external visual representations tend to support learning, their effects are influenced by a variety of factors such as the alignment between key representational features and the learning goals, the saliency to the learner of key elements in the representations, and students' prior knowledge and ability to identify and process explicit and implicit information included in the visualization.

Many visual representations used in chemistry are included in textbooks to help students develop mental images of the submicroscopic world. Chemical scientists rely on a variety of visual representations of particulate entities and the processes in which they are involved to make predictions, build explanations, and construct arguments about the properties of systems of interest.[7,8] In particular, visual representations support experts' mechanistic reasoning in which the properties and interactions between the submicroscopic components of a system are used to build causal stories to make sense of observed macroscopic properties, events, and behaviors.[2]

Seeking to better understand how visual representations may influence, support, or hinder students' mechanistic reasoning, we carried out a qualitative research study designed to explore differences in the types of reasoning triggered by information presented to chemistry students in two different formats. One group of students was asked to analyze a sequence of images designed to represent the submicroscopic components of a chemical system, as well as their properties and interactions. Another group of students was asked to read and analyze a short text that described those same components, properties, and interactions and included the same images distributed in proper places along the narrative. Our results reveal important differences in how students reason about chemical phenomena under the two conditions, and provide insights into how to use textual and visual information to better support student mechanistic reasoning in chemistry.

■ USING VISUAL REPRESENTATIONS

A variety of research studies have elicited several advantages in using external visual representations to support learning and understanding.[1−8] These advantages are most significant when such representations match or are aligned with the learning demands of the task at hand. Visual representations may help

Received: September 17, 2017
Revised: November 23, 2017
Published: December 21, 2017

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

reduce the cognitive effort required to solve a problem by, for example, grouping together information and facilitating search and recognition. Visualizations can also help externalize or make explicit abstract information, or they may focus learners' attention and limit the range of inferences that they can make about the concepts that are represented.[9,10]

Unfortunately, the benefits of visual representations do not come free of challenges. Students must know how to read and decode the information that is represented and understand how the visualization relates to what it tries to represent.[11] Novice learners often focus their attention on the most explicit visual attribute of a representation, ignoring other features that may be more significant or relevant.[12] Attending to the less explicit elements often demands that the learner meaningfully understands the concepts or ideas that are represented and the relationships between them.

Research conducted in the past 25 years has shown that large learning gains may result from instruction that combines visual external representations and written descriptions.[13] This learning benefit is known as the multimedia effect. However, the mere presence of text and images does not guarantee increased comprehension particularly when the visual representation includes distracting elements that may be interesting but are irrelevant for instruction (coherence effect). These results are commonly explained using models of multimedia learning that propose the existence of separate cognitive channels for processing verbal and visual information.[14]

Work in the areas of multimedia learning and visual perception has elicited key elements to be considered in the selection or design of visual representations to support learning.[13,14] First, the mental model and type of reasoning that the visual representation should support need to be clearly defined and specified. Different representations of the same system or phenomenon may lead to the creation of different mental models or ways of reasoning. A second consideration is the nature of the design elements that will more effectively guide student attention to relevant information. The selection of these elements depends on the learning goals and the role that the representation plays within the educational resource. Additionally, one must reflect on how students' prior knowledge, experiences, and intuitive reasoning may influence their processing of the information that is represented.

■ LEARNING FROM TEXTS

The processing of texts demands both comprehension of the information presented and integration of this information with the reader's background knowledge.[15] Most theoretical models of learning from texts suggest that reading comprehension requires readers to construct a coherent mental representation that captures the actual meaning of the text. To build a successful representation, readers should be able to meaningfully connect core elements in the text and incorporate their background knowledge to build a mental representation that provides an interpreted description of what is read. The construction of an appropriate mental model requires active inferencing and adequate prior knowledge.[16]

Due to working memory limitations, readers are not likely to attend to all elements in a text. During reading, the contents of the readers' working memory are continually refreshed. Consequently, relationships between elements in a text are more likely to be established if these elements are activated at the same time.[15] The creation of effective relations between elements in a text is thus affected by text organization and verbal complexity, which influence what elements are activated and when this happens. A reader's prior knowledge also affects the quality of the connections that are established, making the best format of texts dependent on the nature of the audience. Readers with weak background knowledge frequently benefit from a highly coherent text, while readers with stronger backgrounds remember more from somewhat incoherent texts that stimulate active processing during reading.[17,18]

Supplemental elements, such as images or activities, foster learning from texts if they increase the probability of simultaneous activation of the information to be connected.[19] Pictures support comprehension when they facilitate and foster the construction of a task-appropriate mental representation.[20,21] The impact is more significant for readers who have low prior knowledge but high spatial cognitive abilities. The positive effects of embedded images on text recall and comprehension increase when these visualizations serve interpretational (facilitate understanding of abstract concepts) or transformational (facilitate specific cognitive processes) functions.[22] In chemistry education, existing research highlights the benefits that the incorporation of visual representation of chemical entities and phenomena have on students' ability to correctly answer questions, solve problems, and build reasonable explanations.[1−8] Less information exists on the extent to which visual representations, or the combination of these visualizations and text, support mechanistic reasoning in chemistry. Our study was designed to increase our understanding in this regard.

■ MECHANISTIC REASONING IN CHEMISTRY

Mechanistic accounts of events or phenomena invoke the existence of specific agents or components (e.g., atoms, ions, molecules) with particular properties (e.g., mass, charge, size, electronegativity) that determine how the agents interact with each other and the types of processes or activities in which they participate.[23] Analyses of mechanistic reasoning in different domains rely on the characterization of the types and nature of the entities or components that individuals invoke when building arguments or explanations, the properties of the components that are taken into account, the structure and organization assigned to these components, the actions or activities such components are assumed to engage, and the associations or causal relationships that are identified as responsible for their behaviors.[23,24] A similar type of analytical framework has been used by researchers interested in the characterization of student understanding of complex systems.[25]

In chemical thinking, mechanistic reasoning is often based on the analysis of the composition and structure of submicroscopic components of a system that are used to build causal links or stories connecting the properties and behaviors of such components to the observed properties and behaviors of the system at the macroscopic level (i.e., build structure−property relationships). Research in chemistry education has shown that students often struggle to build these types of mechanistic accounts.[26−28] Student thinking is often guided by noncanonical schemas that implicitly give priority to chemical composition over molecular structure, and linear causality over probabilistic causality in the explanation, prediction, and justification of the properties of substances. The construction of mechanistic explanations in chemistry is complex as it requires differentiating concepts defined at diverse scales, integrating different types of knowledge, and identifying and evaluating the effects of multiple variables that may affect the behavior of a system.[29]

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

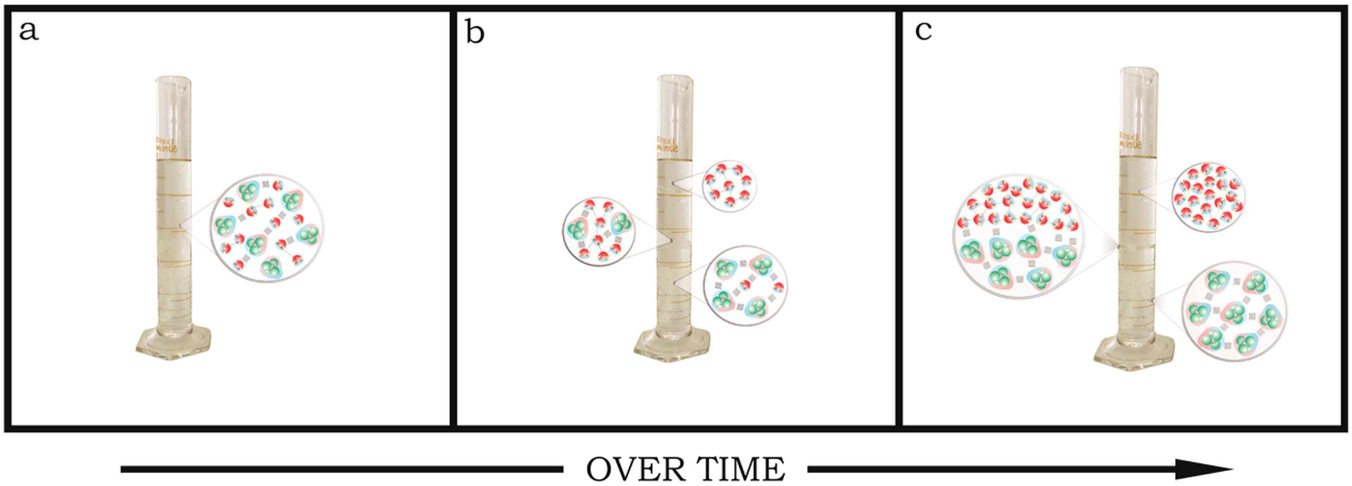


Figure 1. Representative image used in the research instruments.

RESEARCH MOTIVATION AND QUESTIONS

This study is part of a broader project that seeks to improve the quality of chemistry textbooks in Brazil to support meaningful learning. In particular, the project enriches our understanding of how static images can be used alone or in combination with text to better support learning. A critical component of this broader investigation involves exploring differences in how students reason about a phenomenon represented and explained in two different ways: (i) solely through a set of sequential images and (ii) with the use of an illustrated text. Characterizing and understanding these differences can help us improve the integration of textual and visual components in diverse educational resources. In this contribution, we seek to answer the following research questions:

- What are the characteristics of the elements students attend to when interacting solely with images and when interacting with an illustrated text?
- What types of reasoning are expressed by students while engaged in making sense of a phenomenon when interacting solely with images and when interacting with an illustrated text?

METHODS

Context and Participants

This study was carried out in a large, public university in the southwest part of the United States. The Department of Chemistry and Biochemistry at this university offers a two-semester general chemistry course for science and engineering majors. Ten students in total (7 female; 3 male) volunteered to participate in this study. These participants were enrolled in the second semester of the general chemistry course and included students with average and above average performance in this class. They were randomly assigned to two different groups, each of them composed of three students with a projected letter grade of A or B, and two students with a projected grade of C. All the participants had already been introduced to the topics of molecular geometry, polarity, intermolecular forces, and solubility in the first semester of general chemistry. All of them consented to participate in the study which was approved by the Human Subjects Committee at the institution.

Research Instruments

Two types of research instruments were developed to carry out the investigation (both are included as Supporting Information). The first instrument was a six-page illustrated text created to introduce basic chemical concepts that can be used to explain the immiscibility of two liquid substances. The central goal of the text was to describe and discuss important relationship between molecular properties (e.g., size, polarity, available configurations) and observed macroscopic behaviors (e.g., immiscibility). The case of water and carbon tetrachloride was used as an anchoring phenomenon to organize the presentation of ideas. The reading highlighted both energetic factors (e.g., types of interactions between molecules) and entropic factors (e.g., number of available configurations) that affected the behavior of the liquids. The text was carefully organized to introduce and discuss one or two basic concepts or ideas per page, using at least one image to illustrate them. A first version of the text was created by the first author of this paper and modified on the basis of discussions with the second author, who teaches general chemistry, and a second general chemistry instructor. The second research instrument included enlarged versions of each of the images presented in the illustrated text, separated in different pages without captions or any other major textual elements. Figure 1 is a representative example of the images included in our research instruments.

Data Collection

All data were collected using individual semistructured interviews that lasted between 20 and 40 min. The types of questions asked during the interviews are included with the corresponding research instruments in the Supporting Information. These questions sought to elicit the nature of the elements students paid attention to and their reasoning about them. During their individual interview, each of the students in one group was presented with the illustrated text and asked to read the first page. After completing this reading, the interviewer asked students to summarize the content of the page and to discuss what they had learned about the phenomenon under analysis (i.e., immiscibility of water and carbon tetrachloride). If needed, the interviewer directed students' attention toward a particular feature that they had not spontaneously considered in their analysis of the text or associated images, asking them to discuss it. The same process was repeated with each of the six pages of the illustrated text. Once interviewees finished the

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

analysis of the last page, they were prompted to generate an explanation for the immiscibility of the two liquids based on what they had learned.

Students in the other group were individually presented with the first image included in the second research instrument and asked to interpret it. If needed, the interviewer directed students' attention toward a particular feature that they had not spontaneously considered on the image under analysis, asking them to discuss it. This same process was repeated with each of the images, which were presented one at a time in the same sequence as they appeared in the illustrated text. Once interviewees finished their analysis of the last image, they were prompted to generate an explanation for the immiscibility of water and carbon tetrachloride based on what they had learned.

Data Analysis

All interviews were transcribed verbatim and analyzed using a constant comparison approach. For confidentiality purposes, the interview transcripts were given a simple label from S1 to S10. Before looking at the data, the authors met to discuss and agree upon general and specific areas of attention based on the goals of the study and our analytical framework. Then, the first author of this paper read and analyzed one of the transcripts, generating and applying codes in alignment with the specified analytical targets. This first analysis was discussed with the other authors and modified until complete agreement. The modified coding scheme was then used by the first author to guide the analysis of a second interview transcript, followed by discussion with the other authors until complete agreement. This process led to the modification and enrichment of the coding scheme, and was reapplied in a systematic manner to analyze all the interview transcripts from both groups of participants.

The focus of our analytical work was on the identification of major elements in students' descriptions and analyses of the information provided. Given our interest in characterizing mechanistic reasoning, we paid close attention to the types of components, properties, interactions, and causal relationships our participants noticed. During our analysis, we recognized the importance of differentiating between compositional and structural elements highlighted by the participants. We also analyzed the descriptions that students built of what they noticed and the inferences they made on the basis of the information provided and their background knowledge. As a result of our discussions, we recognized the need to pay closer attention to the extent to which participants adopted a more descriptive or interpretive stance when analyzing a given image or text page. Our coding approach is illustrated in the Supporting Information, where we present representative segments of interview transcripts and the associated analyses. Critical review of each of the detailed analytical logs generated for each of the participants led us to the identification of the major findings described in the following section.

■ MAJOR FINDINGS

The research findings summarized in the following paragraphs correspond to major trends that emerged from the analysis of each of the two sets of interviews. In particular, we highlight features and reasoning patterns that were identified in at least half of the interviews in any given set.

Sequence of Images

The analyses generated by study participants interviewed using the sequence of images included in our research instrument shared various characteristics. In general, these analyses were more descriptive of elements present in the different images than interpretive of their meaning, and students often focused on the description of a single salient feature in each representation. For example, they noticed the meniscus between the two liquids shown in the first image, they paid attention to the difference in color between represented particles in the second image, and they highlighted the difference in molecular sizes in the seventh image. When prompted, most students were capable of recognizing and properly interpreting other features in most representations, but many of them stopped their spontaneous analysis after the description of a sole feature.

Some types of representational features seemed more salient than others to students in this group. References to differences in color, size, position, and number of particles were more common than references to differences in molecular geometry, relative orientation between molecules, or interactions between them. This suggested a more prevalent attention to compositional elements in the representations than to structural factors. This bias in attention was observed across different representational scales. For example, at the multiparticle scale, when looking at the representation of collection of molecules of water and carbon tetrachloride in the sixth image, most students described differences in the composition of each phase without noticing differences in relative molecular orientations across the system. Similarly, at the single-particle scale, when comparing single molecules of H_2O and CCl_4 represented in the third image, participants more frequently mentioned differences in composition than in structure. Box 1 includes representative excerpts illustrating the focus on composition over structure in the analysis of Figure 3 (as numbered in the protocol, see Supporting Information), where the actual structure of the molecules of water and carbon tetrachloride is first introduced.

Box 1. Initial Elements Noticed by All Participants in the "Only Images" Group During Their Analysis of Figure 3, Which Introduced the Structure of H_2O and CCl_4 Molecules

I: What do you think this image (Figure 3) represents?
S1: It looks like they were different substances, and the second set of bubbles indicates which actual molecules there are exactly which different substances.
S2: The composition of each substance in this previous image, as just like these are two separate molecules and shows what these molecules are.
S3: The top is water and the bottom is tetrachloride... the red is water and the blue means tetrachloride. And they're not mixing.
S4: It is shows more specifically that the top molecules are water molecules, and the bottom is carbon tetrachloride.
S5: The top liquid is water and the bottom one is the CCl_4. And each of these dots represents one of these things.

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

Some images in the research instrument included symbolic labels (i.e., $\delta+$, $\delta-$) in combination with color coding (i.e., blue, red) to provide information about partial charges in molecules (see eighth image in the research instrument). These two cues were used by all participants to make claims about attractive molecular interactions. Their arguments, however, often revealed a lack of differentiation of the various types of intermolecular forces. Most participants in this group generated correct interpretations based on electrostatic interactions between sites with opposite partial charge, but were unable to differentiate one type of intermolecular force from another on the basis of the representations provided. Consider this exchange in which the interviewer was exploring (without success) whether the student could identify the hydrogen bonding interaction:

I: Okay. And in this one?
S2: It shows like specifically the hydrogen that is positive interacting with the negative oxygen
I: What is the meaning of the dotted line?
S2: The line is just showing how they interact with each other
I: Do you know what type of interaction this is?
S2: mmm... like electrostatic interaction, by charge

In general, the visual saliency of the color-coded distribution of charge in polar (water) molecules led several students to pay more attention to this feature and to assume that such polar interactions were mostly responsible for the immiscibility of the two substances. This type of reasoning is illustrated by the following excerpts:

S2: In a very large time we get a complete homogenization on the top and on the bottom... There's very clearly like water on the top and carbon tetrachloride on the bottom because of the way they interact. I guess the polarity, like polarity of the molecules.
S3: Water it is really negative on one side so, it is really going to be attracted to itself, like to other water molecules because it is polar; like one side is really negative and the other side is positive... this is why I think they're not mixing.

Some symbolic elements included in the images used in our study, such as arrows or lines between molecules, were given non-normative interpretations that revealed mechanistic confusion. For example, some students interpreted bond dipole arrows (fourth figure) as indicative of flow of electrons from one atom to another:

I: What is the meaning of these arrows?
S1: The direction that the negative charge density moves toward.

Similarly, lines between molecules representing attractive interactions (eighth figure) were interpreted by some students as indicative of molecular movement:

I: What is the meaning of this dotted line?
S4: I think it is signifying they're gonna move together; they can attract each other because it is the only way they could collide.

In general, these confusions did not have a major effect on students' interpretation of the phenomenon under analysis.

Students in this group did not spontaneously make references to interactions between the represented particles until such interactions were made explicit in the eighth figure. However, most of the participants directly or indirectly referred to those interactions in their analysis of the separation over time of the two liquids as represented in the last figure or in their final explanation of the target phenomenon. These final explanations were quite varied, though. Some of them were more mechanistic in nature, including references to factors recognized through the interpretation of the different images (e.g., difference in charge distribution, difference in strength of interactions). The following excerpt is representative of these types of explanations:

I think because the carbon tetrachloride charges are more evenly distributed, but water is really negative on one side so, it is gonna attract the really positive side and then, it is gonna attract with itself, like other water molecules; because it is polar, like one side is really negative and one side is positive. (S3)

But other explanations were simply based on references to known rules used in chemistry to justify mixing behaviors (e.g., like-dissolves-like, polar does not mix with nonpolar), without building any causal arguments:

I'll really explain it based on that the CCl_4 overall is a nonpolar molecule and water molecules are polar and so, they do not mix because polar mixes with polar. (S5)

Although most students in this group were able to interpret and make sense of the majority of the images presented to them, they often failed to integrate the concepts and ideas illustrated in each of these images when building an explanation of immiscibility. Some participants expressed memorized structure−property associations, and others built simple mechanistic explanations based on a single causal factor somehow related to the strength of intermolecular interactions.

Illustrated Text

The analyses generated by students who were asked to read the illustrated text were less descriptive and more interpretive than those developed by the students who solely had access to the images. This may have been due to the great difference in the amount of information available to participants in each group. There were, however, similarities in performance that may be indicative of reasoning patterns common among the targeted population of students.

Most students in the "illustrated text" group identified and discussed the different factors introduced in every page of the text without the need of much prompting. The ideas expressed by these participants appeared mostly derived from both the written text and their prior knowledge, with little spontaneous reference to the associated images. Students in this group more frequently highlighted both compositional and structural features when completing their analyses than students in the "only images" condition. In the presence of an accompanying text, salient visual features in the embedded images seemed to have much less influence on students' expressed reasoning.

Interestingly, the larger number of concepts and ideas brought to the forefront in the analysis of the reading created challenges in interpretation that several participants were unable to resolve. Students used several of the concepts introduced in the reading without much differentiation or precision in their application. For example, several of them would refer to the "electronegativity of molecules" or to the "polarity of atoms", and would use the terms electronegativity, polarity, and partial charge in interchangeable ways. The following excerpt illustrates these types of conceptual confusions:

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

I would say it is mostly because of how polar and nonpolar they are... if there's a nonpolar and there's a polar solution, the polar solution is gonna likely stay with itself and the nonpolar would like to stay with themselves... I do not know if it is between two polars, then it might mix because the polarity can connect... I think it is mostly because of the polarity caused by the hydrogen bonding, dispersion, and the dipole−dipole moments. (S9)

The text facilitated the recognition of relevant differences, such as differences in molecular structure and polarity, and differences in the types of intermolecular forces acting between various molecules (i.e., dispersion, dipole−dipole, and hydrogen bonding interactions). However, the understanding of such differences and their causes was limited. In most cases, students were unable to articulate the connections between the internal structure of a system at one scale (e.g., distribution of electrons among different atoms in a molecule) and the properties of a system at another (e.g., molecular polarity).

Some students in this group introduced ideas that were not actually present in the text when completing their analyses. These additions were often about the relative importance of one factor over another when analyzing molecular interactions, such as claiming that dispersion forces were the weakest interactions and hydrogen bonding was the strongest, or stating that the effects of partial charges on intermolecular interactions were more important than effects due to differences in molecular size. Compared to the set of sequential images, the illustrated text seemed to more easily trigger prior knowledge and beliefs that were interspersed with the discussion of the actual content of the reading.

Participants' explanations of the immiscibility of water and carbon tetrachloride generated at the completion of the reading were mechanistic in nature. Nevertheless, as observed in the "sequence of images" group, most of these mechanistic explanations relied on a single causal factor (typically the difference in the nature or strength of intermolecular forces between particles) to explain the observed behavior. The following excerpt illustrates this type of reasoning:

It does not mean water do not want to interact with the carbon tetrachloride, but water is going to interact better with itself than with the other molecule... because of the different IMFs water is going to have, like hydrogen bonding with other water molecule, and both dipole−dipole moments as well as dispersion. (S7)

Only one student in this group explicitly referred to other relevant structural features, such as the small size of the water molecules, when generating the final explanation. Although the text explicitly highlighted the importance that configurational factors had in determining the immiscibility of the two liquids, none of the participants paid much attention to that information. Proposed mechanisms were static interaction-based accounts in which dynamical configurational factors described in the reading were filtered out.

DISCUSSION

Our study revealed major differences but also important similarities in student reasoning when making sense of a phenomenon using solely a sequence of images or an illustrated text. Analyses of images by our study participants were mostly descriptive and focused on a single salient feature, typically of compositional nature. Attention to structural features was more limited. However, students were able to generate simple but normative interpretations of a variety of features when prompted during the interview. On the other hand, analyses of the illustrated text included richer interpretations that referenced relevant compositional and structural factors discussed in the reading. Nevertheless, these interpretations often revealed conceptual confusions and undifferentiation of concepts, and were affected by students' prior knowledge and beliefs. More participants under the "illustrated text" condition built mechanistic explanations of the target phenomenon (liquid immiscibility) than students in the "sequence of images" case. However, in both cases, these mechanistic explanations invoked a single causal factor as responsible for the phenomenon. Such a factor typically referred to the nature or strength of the interactions between different components. Configurational effects, although explicitly mentioned in the reading and implicitly represented in the images, were neglected.

Students who completed the reading made few explicit references to the images embedded within the text. When prompted, they would talk about the images, state that they paid attention to them, and claim that these representations were useful in making sense of the content while completing the reading. However, it was not possible to evaluate the actual extent to which the images affected students' interpretations of the content presented in each page. On the basis of our findings from the two sets of interviewed students, we speculate that the images took a secondary place in students' analyses in the presence of accompanying text. Visually salient features in each of the images had a much lesser influence on students' analyses in the "illustrated text" condition than in the "sequence of images" case.

Our findings also highlight the difficulties that students face to build mechanistic explanations that take into account the various factors that commonly determine the properties and behaviors of chemical systems. Students' tendencies to reduce the number of variables to consider when making predictions or building explanations have been reported in past studies.[30] Prior research studies have also shown that there are implicit biases that often lead students to emphasize the actions of causal agents that act on others through direct interactions, neglecting probabilistic effects that emerge from random phenomena.[31,32] These constraints in student reasoning seemed to affect the interpretations and explanations built by our study participants. Although the reading used in our investigation was designed to explicitly discuss some probabilistic effects that are important in explaining liquid immiscibility, this information seemed to have little influence on students' thinking as elicited by the resources and prompts used in this study. Reliance on static images in both research instruments may have been partially responsible for this outcome, as other authors have reported positive effects in student reasoning about emerging phenomena using dynamic simulations.[33] This is an area in which further studies in chemistry education are needed in order to learn how to best support, and trigger, student ability to generate mechanistic accounts of physical and chemical phenomena.

IMPLICATIONS

Although students' interpretations and explanations when working solely with images were limited and strongly influenced by the most salient features in the representations, the generated analyses were less prone to conceptual confusion. Additionally, images were less likely to trigger prior knowledge and beliefs that somewhat interfered with the analysis of the available information. These findings suggest that engaging students in

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

the analysis of sequential images designed to highlight core elements in the explanation of a phenomenon may have pedagogical advantages. Using these types of images as a first approach in the analysis of a system or phenomenon can serve both as eliciting and scaffolding tool. The analysis and discussion of students' descriptions and interpretations as they work with images could help make visible the features to which they pay attention and those that they ignore. This information would be useful to plan further instruction. Engagement with the images could also help prime student thinking for the concepts to be discussed in class. Additional benefits for students working with diagrams have been highlighted by other authors.[34]

Our findings also suggest that educators likely overestimate the effectiveness of illustrated texts in helping students meaningfully understand and apply the different concepts and ideas used in chemistry to build connections between the submicroscopic structure of a system and its emerging properties at the macroscopic scale. Most participants in our study were unable to disentangle the variety of concepts introduced in the reading (i.e., electronegativity, charge distribution, bond polarity, molecular polarity, intermolecular forces) and to integrate them in a productive way to make sense of a phenomenon. As reported by study participants, images may have aided in the meaning making process. However, they did not resolve conceptual confusions. Although our findings do not provide a solution to this challenge, they point to the need for the careful development of illustrated texts to open more opportunities for the elaboration of single concepts, to compare and contrast related concepts to support differentiation, and to meaningfully integrate the text with the images to compel and challenge students to engage in the interpretation of both.[35]

■ LIMITATIONS

The conclusions of this work should be taken cautiously given inherent limitations in our methodology. This was an exploratory study that included a small number of volunteer participants, with an average or above average performance in their general chemistry course. Thus, their reasoning and behavior may not have been representative of the population of students taking this course. Additionally, these students were asked to complete a task in an individual interview setting, which was likely quite different from the actual environments in which they may engage with texts or images when studying for a course. On one hand, the research instruments and environment may have prompted some students to pay closer attention to the information provided than they normally do under real conditions. On the other hand, our research tools and approach may have constrained student reasoning and limited our ability to explore our participants' thinking and understanding. Further studies are needed to explore how the nature of the media and interview prompts affect student reasoning and response processes. Characterizing both the affordances offered and the constraints imposed by different educational resources and approaches on student reasoning is critical for designing more effective tools and learning environments.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.7b00716.

Text and images interview protocol, including the general questions posed during the semistructured interviews (PDF)

Image only interview protocol, including the general questions posed during the semistructured interviews (PDF)

Representative examples of the coding approach used in this qualitative study (PDF)

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: karinascalco@gmail.com.

ORCID

Karina C. Scalco: 0000-0002-4882-3618
Vicente Talanquer: 0000-0002-5737-3313

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors acknowledge the support from the Brazil government and CAPES − Coordination for the Improvement of Higher Education Personnel, which made possible their collaboration.

■ REFERENCES

(1) Jones, L. L.; Kelly, R. M. Visualization: The Key to Understanding Chemistry Concepts. In *Sputnik to Smartphones: A Half-Century of Chemistry Education*; Orna, M. V., Ed.; ACS Symposium Series Vol. *1208*; American Chemical Society: Washington, DC, 2015; Chapter 8, pp 121−140.

(2) *Multiple Representations in Chemical Education*; Gilbert, J. K., Treagust, D., Eds.; Springer: Dordrecht, The Netherlands, 2009.

(3) Williamson, V. M. Teaching Chemistry with Visualizations: What's the Research Evidence? In *Investigating Classroom Myths through Research on Teaching*; Bunce, D., Ed.; ACS Symposium Series Vol. *1074*; American Chemical Society: Washington, DC, 2011; Chapter 6, pp 65−81.

(4) Wu, H. K.; Shah, P. Exploring Visuospatial Thinking in Chemistry Learning. *Sci. Educ.* **2004**, *88*, 465−492.

(5) *Visualization in Science Education*; Gilbert, J., Ed.; Springer: Dordrecht, The Netherlands, 2005.

(6) *Visualization: Theory and Practice in Science Education*; Gilbert, J., Reiner, M., Nakhleh, M., Eds.;Springer: Dordrecht, The Netherlands, 2008.

(7) *Constructing Representations to Learn Science*; Tytler, R., Prain, V., Hubber, P., Waldrip, B., Eds.; Springer: Dordrecht, The Netherlands, 2013.

(8) Evagorou, M.; Erduran, S.; Mäntylä, T. The Role of Visual Representations in Scientific Practices: From Conceptual Understanding and Knowledge Generation to 'Seeing' How Science Works. *Int. J. STEM Educ.* **2015**, *2*, 11.

(9) Scaife, M.; Rogers, Y. External Cognition: How Do Graphical Representations Work? *Int. J. Hum-Comput. St.* **1996**, *45*, 185−213.

(10) Mathewson, J. H. Visual-Spatial Thinking: An Aspect of Science Overlooked by Educators. *Sci. Educ.* **1999**, *83*, 33−54.

(11) de Vries, E.; Demetriadis, S.; Ainsworth, S. External Representations for Learning. In *Technology-Enhanced Learning*; Balacheff, N., Ludvigsen, S., de Jong, T., Lazonder, A., Barnes, S., Eds.; Springer: New York, NY, 2009; pp 137−154.

(12) Kozma, R. The Material Features of Multiple Representations and their Cognitive and Social Affordances for Science Understanding. *Learn. Instr.* **2003**, *13* (2), 205−226.

(13) Mayer, R. E. *Multimedia Learning*; Cambridge University Press: Cambridge/New York, 2001.

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354

(14) Mayer, R. E. Principles for Reducing Extraneous Processing in Multimedia Learning: Coherence, Signaling, Redundancy, Spatial Contiguity and Temporal Contiguity Principles. In *The Cambridge Handbook of Multimedia Learning*; Mayer, R. E., Ed.; Cambridge University Press: Cambridge, 2005; pp 182−200.
(15) van den Broek, P. Using Texts in Science Education: Cognitive Processes and Knowledge Representation. *Science* **2010**, *328* (5977), 453−456.
(16) Kendeou, P.; van den Broek, P.; Helder, A.; Karlsson, J. A Cognitive View of Reading Comprehension: Implications for Reading Difficulties. *Learn. Disabil. Res.Pr.* **2014**, *29* (1), 10−16.
(17) McNamara, D. S.; Kintsch, E.; Songer, N. B.; Kintsch, W. Are Good Texts Always Better? Interaction of Text Coherence, Background Knowledge, and Levels of Understanding in Learning from Text. *Cogn. Instr.* **1996**, *14*, 1−43.
(18) Kendeou, P.; van den Broek, P. W. The Effects of Prior Knowledge and Text Structure on Comprehension Processes during the Reading of Scientific Texts. *Mem. Cognit.* **2007**, *35*, 1567−1577.
(19) Butcher, K. R. Learning from Text with Diagrams: Promoting Mental Model Development and Inference Generation. *J. Educ. Psychol.* **2006**, *98* (1), 182−197.
(20) Schnotz, W. Towards an Integrated View of Learning From Text and Visual Displays. *Educ. Psychol. Rev.* **2002**, *14*, 101−120.
(21) Schnotz, W.; Bannert, M. Construction and Interference in Learning from Multiple Representation. *Learn. Instr.* **2003**, *13*, 141−156.
(22) Carney, R. N.; Levin, J. R. Pictorial Illustrations Still Improve Students' Learning from Text. *Educ. Psychol. Rev.* **2002**, *14* (1), 5−26.
(23) Russ, R. S.; Scherr, R. E.; Hammer, D.; Mikeska, J. Recognizing Mechanistic Reasoning in Student Scientific Inquiry: A Framework for Discourse Analysis Developed from Philosophy of Science. *Sci. Educ.* **2008**, *92* (3), 499−524.
(24) Bolger, M. S.; Kobiela, M.; Weinberg, P. J.; Lehrer, R. Children's Mechanistic Reasoning. *Cogn. Instr.* **2012**, *30*, 170−206.
(25) Hmelo-Silver, C. E.; Pfeffer, M. G. Comparing Expert and Novice Understanding of a Complex System from the Perspective of Structures, Behaviors, and Functions. *Cogn. Sci.* **2004**, *28*, 127−138.
(26) Cooper, M. M.; Corley, L. H.; Underwood, S. M. An Investigation of College Chemistry Students' Understanding of Structure−Property Relationships. *J. Res. Sci. Teach.* **2013**, *50*, 699−721.
(27) Maeyer, J.; Talanquer, V. Making Predictions About Chemical Reactivity: Assumptions and Heuristics. *J. Res. Sci. Teach.* **2013**, *50*, 748−767.
(28) Talanquer, V. How Do Students Reason About Chemical Substances and Reactions? In *Concepts of Matter in Science Education*; Tsaparlis, G., Sevian, H., Eds.; Springer: Dordrecht, The Netherlands, 2013; pp 331−346.
(29) Talanquer, V. Progressions in Reasoning about Structure-Property Relationships. *Chem. Educ. Res. Pract.* **2017**, DOI: 10.1039/C7RP00187H.
(30) Maeyer, J.; Talanquer, V. The Role of Intuitive Heuristics in Students' Thinking: Ranking Chemical Substances. *Sci. Educ.* **2010**, *94*, 963−984.
(31) Talanquer, V. Common Sense Chemistry: A Model for Understanding Students' Alternative Conceptions. *J. Chem. Educ.* **2006**, *83* (5), 811−816.
(32) Chi, M. T. H.; Roscoe, R. D.; Slotta, J. D.; Roy, M.; Chase, C. C. Misconceived Causal Explanations for Emergent Processes. *Cognitive Sci.* **2012**, *36* (1), 1−61.
(33) Levy, S. T.; Wilensky, U. Crossing Levels and Representations: The Connected Chemistry (CC1) Curriculum. *J. Sci. Educ. Technol.* **2009**, *18* (3), 224−242.
(34) Ainsworth, S.; Loizov, A. T. The Effects of Self-Explaining when Learning with Text or Diagrams. *Cognitive Sci.* **2003**, *27*, 669−884.
(35) Rau, M. A, Enhancing Undergraduate Chemistry Learning by Helping Students Make Connections Among Multiple Graphical Representations. *Chem. Educ. Res. Pract.* **2015**, *16*, 654−669.

DOI: 10.1021/acs.jchemed.7b00716
J. Chem. Educ. 2018, 95, 347−354