Students’ Predictions About the Sensory Properties of Chemical Compounds: Additive Versus Emergent Frameworks

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ABSTRACT: We investigated general chemistry students’ intuitive ideas about the expected properties of the products of a chemical reaction. In particular, we analyzed college chemistry students’ predictions about the color, smell, and taste of the products of chemical reactions represented at the molecular level. The study was designed to explore the extent to which novice learners intuitively use an additive framework to predict the properties of the product, rather than an approach that recognizes the emergent nature of the properties of chemical compounds. To this end, we used a mixed-methods research approach based on answers to multiple-choice questions and individual interviews with students enrolled in the first year of an introductory general chemistry course for science and engineering majors. Our results indicate that most students at this level rely on an additive heuristic to predict the properties of chemical compounds, overlooking the possibility of emergent properties resulting from the interaction of the atoms that compose the system. Chemistry instructors and chemical educators thus need to intentionally design learning opportunities for students to recognize and differentiate additive and emergent properties in a variety of contexts.

INTRODUCTION

Commonsense reasoning seems to play a central role in many of the naïve explanations that novice science students build about natural phenomena (Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Talanquer, 2006; Viennot, 2001). This type of reasoning is grounded in a set of presuppositions about the surrounding world and the nature of things and relies on mental strategies to make decisions and build inferences based on the information that is readily available (Campanario & Otero, 2000; de Cudmani, Pesa, & Salinas, 2000; Furió & Furió, 2000; Hilton, 2002; Pozo &
Gómez-Crespo, 1998). Intuitive or commonsense thinking help us simplify the complexity of the problems or tasks we face in our daily lives without demanding too much intellectual effort. However, it may also mislead novice science learners in the identification of the relevant variables, properties, or interactions that determine the behavior of natural systems.

On the basis of the empirical evidence accumulated over the past 30 years on students’ alternative conceptions in chemistry (Barker, 2000; Duit, 2004; Garnett, Garnett, & Hackling, 1995; Nakhleh, 1992; Taber, 2002), we have recently identified a set of presuppositions (empirical assumptions) and reasoning strategies (reasoning heuristics) that seem to underlie many of the alternative conceptions of naïve chemistry students (Talanquer, 2006). According to our analysis, many beginning chemistry students have a philosophical view of the world closely related to naïve realism (Driver et al., 1985; Furió & Furió, 2000; Hayes, 1979; Pozo & Gómez-Crespo, 1998; Viennot, 2001). Within this stance, these “intuitive chemists” demonstrate extreme confidence in the senses as instruments for research and analysis of material properties and natural phenomena. Their vision of the world is supplemented by a set of intuitive assumptions about the nature and properties of chemical substances and processes and by a set of heuristics that guide and constrain their reasoning (Talanquer, 2006).

The empirical assumptions and heuristics that guide the reasoning of an intuitive chemist are certainly interrelated and may be activated simultaneously when he or she faces a challenge, looks for an explanation, or makes a decision. However, the identification of specific assumptions and heuristics can facilitate the analysis of the learning difficulties that beginning chemistry students face when trying to reconcile their personal view and the scientific view of the world. On the basis of these ideas, in this paper we explore novice chemistry students’ commonsense reasoning about the expected properties of the products of a chemical reaction. In particular, our study focuses on the analysis of the predictions of college chemistry students about the color, smell, and taste of the products of chemical reactions represented at the molecular level. In this investigation, we explore the extent to which novice students intuitively use an additive framework to predict the properties of the product, rather than an approach that recognizes the emergent nature of the properties of chemical compounds.

**ADDITIVE VERSUS EMERGENT PROPERTIES**

The term “emergent property” traditionally refers to those properties of a composite system that result from the interaction between its parts, but differ from those of the individual components. These types of properties differ from “additive properties,” such as the mass or the electrical charge of a system, that result from the addition or linear combination of the original properties of each component. Emergent properties cannot be easily predicted based on the properties of the individual parts, and they disappear when the system is disassembled or reorganized. Although in the past few years, it has become a practice to use the term “emergent property” to refer to the properties of complex nonlinear systems (Jacobson & Wilensky, 2006; Wilensky & Resnick, 1999), the fact is that “emergence” is a central chemistry concept (Luisi, 2002). The chemical properties of a single atom are emergent from those of the composing electrons, protons, and neutrons; the chemical properties of a molecule (compound) are emergent from those of the atoms in the system (elements), and many of the properties of a liquid are emergent with respect to those of the individual molecules that compose the fluid.

The concept of “emergence” can be also applied to refer to emergent processes in a system (Chi, 2005). In this case, we consider processes that result from the simultaneous,
and often random, interactions between the system’s components. These are processes that emerge from the collective and continuous interaction among parts in a system, and do not follow a determined causal sequence. A typical example of these types of processes is the diffusion of a gas in another fluid, which results from the random movements and interactions among all particles in the system; chemical equilibrium is another good example of an emergent process. In contrast, we can identify “direct causal processes” in systems where the behaviors of the various constituent components are quite distinct and their interactions tend to be sequential, inter-dependent, and constrained. Blood circulation in our bodies is a representative example of direct processes.

Chi (2005) has suggested that students should be expected to have more robust alternative conceptions about emergent processes than about direct causal processes, given that intuitive thinkers most likely will classify natural processes in the latter category. According to Chi, students that misclassify diffusion as a causal direct process perform an ontological miscategorization and will have serious difficulties in understanding the actual underlying mechanism. From our perspective (Talanquer, 2006), such difficulty arises from the intuitive application of the empirical assumption of mechanical causality (Andersson, 1986; Gutierrez & Ogborn, 1992; Viennot, 2001) and the linear sequencing heuristic (Driver, Guesne & Tiberghien, 1985; Viennot, 2001). For the intuitive thinker, changes or processes in a system are induced by an active agent (single mechanical cause) that acts upon a passive body inducing a sequence of events in which the different parts involved intervene one by one, in specific moments and in a specific progression (linear sequencing). This type of commonsense reasoning has been consistently elicited in a variety of studies focused on students’ understanding of emergent phenomena in complex systems (Jacobson & Wilensky, 2006; Penner, 2000; Wilensky & Resnick, 1999).

The problems students experience in analyzing and understanding emergent processes suggest that they might also have difficulties recognizing, understanding, and predicting the existence of emergent properties in chemical systems. In general, when novice chemistry students face a problem involving several variables or influences, they tend to linearly combine and distribute the effects homogeneously among the different parts in the system (additive heuristic) (Talanquer, 2006). Following Chi’s analysis, we could expect an intuitive chemist to assume that most properties of composite systems, such as chemical compounds, are additive and result from the linear combination of the original properties of the individual components (additive framework). These types of novice learners should have serious difficulties recognizing that many properties, in particular chemical properties, emerge from the interactions among the different components of the system (emergent framework), and thus cannot be easily predicted.

Results from prior research studies on chemistry learning seem to support the idea that novice learners rely on an additive framework when thinking about chemical compounds and reactions. For example, several studies have shown that many students think of chemical compounds as mixtures of elements, and some of them classify homogeneous mixtures as pure substances (Barker, 2000; Stains & Talanquer, 2007; Taber, 2002). Similarly, students find it difficult to differentiate between physical and chemical changes, both at the macroscopic and the microscopic levels (Andersson, 1990; Nakhleh, 1992). Research by Ben-Zvi, Eylon, and Silberstein (1987a) shows that some learners seem to view chemical reactions as additive rather than interactive, and that they conceive molecules as mixtures of atoms rather than as new independent entities. Boo and Watson (2001) indicate that these types of ideas persist even after students complete their chemistry studies. In particular, these authors point out that some students fail to recognize that although atoms involved in a chemical reaction are conserved, their rearrangement into new molecules leads to
substances with different properties. Our study further explores the pervasive nature of some of these ideas.

**METHODOLOGY**

**Research Question**

In this study, we explored college general chemistry students’ predictions about the color, smell, and taste of chemical compounds resulting from the chemical reaction between two substances with specified properties. We specifically targeted student thinking based on microscopic (particulate) representations of chemical systems. This investigation was guided by the following research question:

> What conceptual framework, additive versus emergent, is most commonly used by students to predict the color, smell, and taste of chemical compounds based on their microscopic structure and composition?

Our focus on the prediction of sensory properties, such as color, smell, and taste, was intentional. These types of properties of chemical compounds are not traditionally discussed in introductory chemistry courses, but one should expect that students who truly recognize the emergent nature of chemical properties will not base predictions about sensory properties on an additive framework. Our goal was to minimize the influence of specific domain knowledge or familiarity with the subject on students’ predictions to more clearly assess intuitive reasoning. Given students’ daily experiences with the color, smell, and taste of different substances, sensory properties seemed ideal to explore the influence of common sense reasoning on students’ decisions.

**Instruments and Data Collection**

We followed a mixed method design in which quantitative and qualitative research instruments were used (Greene, Caracelli, & Graham, 1989). The data collection was completed in three main phases: (a) sensory properties questionnaire, (b) interviews, and (c) supplemental studies. Details for each of these phases are presented in the following paragraphs.

a. A sequence of short-response questions was designed to explore students’ ideas about the origin and cause of the color, smell, and taste of natural entities and chemical compounds. Examples of the types of questions used during this part of the study include: Why do lemons smell the way they do? Why don’t they smell like oranges? Why do different substances have different flavors and colors? These exploratory questions were asked during the discussion sessions of the first general chemistry course (GCI) for science and engineering majors at our university (Fall 2004), and the analysis of the students’ responses guided the construction of a short multiple-choice questionnaire that was tested with the same group of students. The results of this test were used to build a revised version of the questionnaire that then served as the main data collection instrument for the present study.

   Our multiple-choice questionnaire (sensory properties questionnaire) included 12 questions that asked students to predict the color, smell, and taste of the chemical compounds resulting from reactions between two substances depicted using
particulate representations. Each of the questions had a molecular image of reactants and products, using circles and spheres of different sizes and colors to represent different types of atoms, together with a description of the relevant sensory properties of the reactants (see Figure 1). These types of representations are very common in modern chemistry textbooks at the high-school and college levels, and they are used on a regular basis in chemistry lectures at our institution. To minimize possible misinterpretations in questions requiring predictions about the color of a chemical product, atoms were represented as black or white circles in all of the questions related to this property.

The questions in the instrument could be divided into three distinct sets, each of them designed to explore students’ predictions about one of three sensory properties (color, smell, or taste) targeted in this study. Each set included four equivalent questions designed to assess the effect of a particular factor on student reasoning. For example, one of the questions had two different groups of particles of equal size reacting in a 1:1 ratio; this question was identified as the reference question of each set. The other three questions in each set illustrated a reaction involving either particles reacting in a different ratio, reacting particles of different sizes, or a reactant that did not have a perceptible sensory property (no color, no smell, or no taste).

The questionnaire was applied in three different GCI classrooms in a subsequent semester (Fall 2005), using a PowerPoint slide show that displayed each question for 15 seconds. For each question, students were asked to select the option that best described the expected properties of the product. The first question in the set was used to explain the nature of the task and to clarify any questions students had about the particulate representations displayed on the screen. Students were told that in each of the questions they had to assume that two different substances with the specified properties had chemically reacted to produce a new chemical compound. Their task was to select the option that described the most likely properties of the chemical product.

b. To gain qualitative insight into the students’ reasoning, short semistructured interviews lasting between 15 and 25 minutes were conducted with student volunteers from general chemistry courses at our university (Fall 2005). During the interviews, participants were presented with each of the 12 questions from our sensory properties questionnaire (displayed on a computer screen), told to select an answer, and then asked to provide a verbal explanation for their choice. All of the interviews began by showing a slide with representations of atoms and molecules similar to those used.

Figure 1. Example of the type of questions included in the sensory properties questionnaire. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
in the study; participants were asked whether they were familiar with these types of images. Then, the first multiple-choice question of the set was displayed and used to clarify any questions the students may have about the nature of the task. Participants were asked to “select the option that described the most plausible properties of the chemical product.” Once an option was selected, the interviewer asked participants to explain their choice. Additional clarification questions were asked when necessary during the process (Why do you think this is the best option? What do you mean by...? Could you tell me more about...?). Each interview was audiotaped, and the students’ explanations were later transcribed.

c. To test the validity and reliability of our results, supplemental studies were conducted in the final stages of our investigation (Spring 2007) using modified versions of the sensory properties questionnaire. These new versions included variations of the multiple-choice options for each question, the replacement of some questions involving chemical reactions with questions depicting the formation of mixtures, and the use of symbolic representations of the chemical reactions instead of particulate ones. These additional tests are described in detail in the section “Supplemental Studies.”

Context and Participants

This study was conducted in a public research institution in the southwest of the United States. This land grant institution has a total current enrollment of over 37,000 undergraduate and graduate students. The chemistry department offers general chemistry courses to over 1,500 students each semester, of whom about 50% are female and nearly 35% are ethnically diverse students with majors ranging from nursing to chemical engineering.

Most of the student participants were enrolled in the first semester of a general chemistry course for science and engineering majors (GCI). This course covers topics such as atomic and molecular structure, states of matter, and chemical reactions (stoichiometry and thermochemistry). The main questionnaire was applied in three different sections of the course, during a class session in the fourth quarter of the academic semester. By then, the central concepts related to properties of chemical compounds and reactions had already been introduced and discussed. A total of 456 individual questionnaires were collected, although not all of the students answered every question. This explains the difference in the total number of answers for each of the questions analyzed in the following section.

The interviews involved 10 student volunteers (eight females and two males) from the GCI classes, where the questionnaire was administered, plus eight additional students (five females and three males) from the second course in the general chemistry sequence (GCII). This second group of students was interviewed at a later time expecting to increase the pool of “expert” thinkers that would better recognize the emergent nature of properties of a chemical product. For reference and confidentiality purposes, a code was created to label each of the interviewees; this code has been used throughout the presentation of our results. The assigned label is based on the type of chemistry course in which students were enrolled and on the order of the interview. For example, interviewee GCI2 refers to the second (2) student in the general chemistry I course (GCI) who completed the interview.

Variations of the sensory properties questionnaire were applied at the end of the first quarter of the academic semester of spring 2007 in two different sections of the GCI course and in one natural science general education course (NATS) at our institution. A total of 428 questionnaires were collected in this supplemental part of the study. The corresponding results support the central claims of our study.
Data Analysis

To develop the final questionnaire, we followed an iterative, nonlinear process to analyze the answers to the sets of short-response questions posed in the first part of the study. Common ideas were highlighted and organized in different categories, which were then regrouped based on identified trends in student thinking. We particularly focused on students’ ideas about the relationship between sensory properties and the composition and structure of chemical substances. The results of this analysis guided the development of a set of multiple-choice questions designed to target what seemed to be relevant factors in student thinking. For example, we identified that some students referred to the size of the atoms or molecules in building their explanations, or to the number of particles of a given species. Thus, we built questions to explore the extent to which these variables were considered important by the majority of the students.

Responses to the sensory properties questionnaire were processed using standard statistical techniques to determine the frequency of selection of the different options associated with any given question. The statistical data were then analyzed to identify major trends in the students’ answers and generate tentative assertions related to our research question. The analysis of the students’ explanations during the interviews was used to validate, enrich, or discard our original interpretations.

RESULTS

The analysis of the data revealed several common trends in the participants’ predictions for all three sensory properties (color, smell, and taste). Thus, to simplify the description and discussion of our results, in this section we use students’ predictions and explanations about the color of a chemical product to describe common patterns of reasoning associated with students’ responses to the sensory properties questionnaire. However, we also highlight the qualitative and quantitative differences in students’ predictions and reasoning about the smell and taste of the product of a chemical reaction. A summary of GCI students’ responses to the sensory properties questionnaire is presented in Tables 1 and 2; these responses were analyzed using a chi-square goodness to fit test to determine whether the observed proportions differed from hypothetical random selection of the different options, or from hypothetical “expert” behavior with over 75% of the participants selecting the correct option. In either case, the observed proportions differed significantly ($p < 0.001$) from the hypothetical results for each of the questions.

Equal Ratio; Equal Size

Question I in Table 1 summarizes GCI students’ predictions about the color of a chemical compound resulting from a 1:1 combination of monoatomic substances with two different colors: blue and yellow. Most of the students in the sample (90.4%, $N = 447$) predicted that the new chemical compound would have a green color, and only 7.61% of the participants indicated that the new substance would likely have a “different” color. Results from the interviews indicated that students who selected option “c” (green color; 60% of GCI and 50% of GCII interviewees) based their predictions on their experiences mixing colors. Many of these students referred to the chemical product as the result of “mixing” two substances and paid attention to the number of atoms of each type of substance to weigh the influence of each color (additive thinking). The following excerpt from a GCI student interview illustrates this type of reasoning:
TABLE 1
Frequency of Responses for the Different Options Associated With Questions About the Color of the Chemical Product of the Reaction Between Two Substances (Sensory Properties Questionnaire)

<table>
<thead>
<tr>
<th></th>
<th>a) Bluish</th>
<th>b) Yellowish</th>
<th>c) Green</th>
<th>d) Other</th>
<th>e) No color</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.671%</td>
<td>0.671%</td>
<td>90.4%</td>
<td>7.61%</td>
<td>0.671%</td>
</tr>
<tr>
<td>II</td>
<td>79.6%</td>
<td>5.17%</td>
<td>7.87%</td>
<td>6.74%</td>
<td>0.674%</td>
</tr>
<tr>
<td>III</td>
<td>50.8%</td>
<td>3.95%</td>
<td>37.6%</td>
<td>6.81%</td>
<td>0.879%</td>
</tr>
<tr>
<td>IV</td>
<td>16.4%</td>
<td>68.7%</td>
<td>9.31%</td>
<td>5.54%</td>
<td></td>
</tr>
</tbody>
</table>

I would choose c) [pause] because there is the same amount of particles of the blue color as of the yellow color, and there are both bonding together with one blue and one yellow so, you know is kind of equal, so both colors are balanced and when blue and yellow are mixed it creates green. (GCI6)

Students who selected option “d” during the interview (other or a different color; 40% of GCI and 50% of GCII interviewees) gave explanations that in many cases indicated recognition of either the emergence of different properties in the formation of a chemical product or the impossibility of predicting the outcome of the chemical reaction based on the information provided. The following excerpts illustrate the reasoning of participants who based their responses on an emergent framework:

If they weren’t chemically bonded then I would just say it’s a mixture of blue and yellow, which would be green, but since they are chemically bonded I think it’s plausible to say they have an entirely different color. So, I’ll select d. (GCII1)

... what I am thinking is that I wouldn’t opt for any of those options because I feel like there is no way for me to know what color that interaction is going to produce. I mean, I’m tempted to say the product has a different color because it seems intuitive that if you mix the two you are going to get something different, but I don’t know that. I don’t know what wavelengths this compound is going to reflect as compared to these two individuals. (GCII7)

However, not all of the students who chose option “d” exhibited this level of expert reasoning. Some of them based their explanations on personal ideas about the relative strength or dominance of one type of color over the other. Consider, for example, the following explanation by interviewee GCI1:

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TABLE 2
Frequency of Responses for the Different Options Associated With Questions About the Smell and Taste of the Chemical Product (Sensory Properties Questionnaire) [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

<table>
<thead>
<tr>
<th>I, N = 452</th>
<th>Mint</th>
<th>Rose</th>
<th>Mint-Rose</th>
<th>Other</th>
<th>No smell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mint</td>
<td>5.97%</td>
<td>3.98%</td>
<td>69.0%</td>
<td>20.6%</td>
<td>0.442%</td>
</tr>
<tr>
<td>Rose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smell?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II, N = 455</th>
<th>Lavender</th>
<th>Cinnamon</th>
<th>Lavender-Cinnamon</th>
<th>Other</th>
<th>No smell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lavender</td>
<td>62.2%</td>
<td>4.83%</td>
<td>18.5%</td>
<td>14.1%</td>
<td>0.439%</td>
</tr>
<tr>
<td>Cinnamon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smell?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>III, N = 451</th>
<th>Lemon</th>
<th>Rose</th>
<th>Lemon-Rose</th>
<th>Other</th>
<th>No smell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemon</td>
<td>25.7%</td>
<td>1.99%</td>
<td>41.2%</td>
<td>30.8%</td>
<td>0.222%</td>
</tr>
<tr>
<td>Rose</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smell?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IV, N = 434</th>
<th>Strong Pungent</th>
<th>Pungent</th>
<th>Other</th>
<th>No smell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pungent</td>
<td>14.8%</td>
<td>56.0%</td>
<td>14.8%</td>
<td>14.5%</td>
</tr>
<tr>
<td>No Smell</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smell?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>I, N = 447</th>
<th>Sweet</th>
<th>Salty</th>
<th>Sweet-Salty</th>
<th>Other</th>
<th>No taste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweet</td>
<td>2.46%</td>
<td>9.40%</td>
<td>59.7%</td>
<td>23.7%</td>
<td>4.70%</td>
</tr>
<tr>
<td>Salty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taste?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>II, N = 453</th>
<th>Sweet</th>
<th>Sour</th>
<th>Sweet-Sour</th>
<th>Other</th>
<th>No taste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweet</td>
<td>45.7%</td>
<td>11.0%</td>
<td>21.4%</td>
<td>20.1%</td>
<td>1.77%</td>
</tr>
<tr>
<td>Sour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taste?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>III, N = 451</th>
<th>Sweet</th>
<th>Sour</th>
<th>Sweet-Sour</th>
<th>Other</th>
<th>No taste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sweet</td>
<td>38.6%</td>
<td>5.90%</td>
<td>42.3%</td>
<td>11.8%</td>
<td>1.33%</td>
</tr>
<tr>
<td>Sour</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taste?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IV, N = 449</th>
<th>Very salty</th>
<th>Salty</th>
<th>Other</th>
<th>No taste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very salty</td>
<td>10.7%</td>
<td>71.9%</td>
<td>10.9%</td>
<td>6.46%</td>
</tr>
<tr>
<td>No Taste</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Taste?</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I know that some colors will overpower each other and some will blend, it is all kind of relative on their chemical compounds and how they react to form other molecules, but [pause] I don’t know [pause] I have to say: a different color, just because blue may be really dominant and yellow may just blend into that. I don’t think it would be green [pause] it’s possible but I don’t think it would go that way. (GCI1)

These types of responses based on personal experience with common materials, such as paints, cooking products, and perfumes, were more commonly present in students’ explanations of the predicted taste or smell of the product of a chemical reaction. For example, of the four GCI interviewees (40%) that predicted that the smell or taste of the
chemical product in the 1:1 reactions between particles of equal sizes would be “different” than that of the reactants or their additive combination (option “d” in questions I in Table 2), three of them built their justifications based on personal beliefs about the strength or power of one type of smell or taste over the other, or on personal cooking or tasting experiences. Only one of the GCI interviewees gave consistent explanations based on scientific understanding of chemical properties. Commonsense reasoning based on the idea of “dominance” was also frequent in students who predicted that the product would have a smell or taste similar to that of one of the reactants (such as salty or minty, for example). The following interview excerpts illustrate this type of thinking:

I think it would be salty [pause] ’cause salt would react with more of the taste buds, [pause]
I don’t know, it would overpower everything. (GCII5)

well, rose once again is still a light smell no matter how much you have of it. Mint is very strong and it’s supposed to kill off other smells too. I would personally think the mint should override the rose; of course you should able to smell the rose but not as strongly as if it was just the pure rose. I would probably smell more of the mint. (GCI4)

The existence of personal ideas about dominant smells and flavors may explain why a larger number of students selected option “d” (other or a different smell or taste) in answering questions I in Table 2 (20.6% for smell, \(N = 452\); 23.7% for taste, \(N = 447\)), compared to the number who chose the equivalent option in the prediction of the color of the chemical product (7.61% in row I in Table 1, \(N = 447\)). Our interview results suggest that it is likely that a significant proportion of these students did not base their response on the application of an emergent framework in the prediction of the properties of the chemical product, but rather were using an additive framework that includes commonsense ideas about some properties being more “dominant” than others. This assumption is further reinforced by the frequent inconsistencies detected in the students’ responses within this set of questionnaires. During the interviews, the few students who demonstrated a solid understanding of the emergent nature of chemical properties (one of ten GCI interviewees and four of eight GCII interviewees) were very consistent in their predictions of the likely outcome of each chemical reaction. On the contrary, students who based their responses on additive reasoning combined with personal ideas about “dominance” of one property over another were rather inconsistent in their predictions. This suggests that consistency of responses within a single questionnaire may serve as an indicator of the type of reasoning that GCI students in the larger sample may have followed.

**Different Ratio; Equal Size**

The students’ tendency to apply an additive heuristic in the prediction of the color of the product of a chemical reaction seems to be confirmed by the answers to the other three questions in the color set. Question II in Table 1 depicts the results for the prediction of the color of a product resulting from the 4:1 combination of monoatomic substances that are blue and yellow, respectively. In this case, a large proportion of the students (79.6%, \(N = 455\)) indicated that the product would have a bluish color (option “a”). This type of answer may be expected from an intuitive thinker who applies an additive rule in which the properties of the product result from the weighted average of the properties of its components. All of the interviewed students who selected this option (90% of GCI and 37.5% of GCII interviewees) used the larger number of blue atoms than yellow atoms as the
main rationale for their predictions. Some of these students also referred to the distribution of atoms in the molecule to justify their answer:

I would say the color is blue because there are more bluish dots than yellow dots, and all the bluish dots are kind of surrounding the yellow, so the yellow won’t be able to come out.

(GCI6)

Similar results were associated with the prediction of the smell and taste of a chemical product resulting from a reaction involving different numbers of atoms of the reacting species (questions II in Table 2). However, in this case the percentage of students selecting option “a,” the answer one may expect from additive thinkers, is lower than that obtained for the prediction of color (79.6% for color, \(N = 455\); 62.2% for smell, \(N = 455\); 45.7% for taste, \(N = 453\)). Our interviews revealed that this difference may be, once again, due to the influence of personal ideas about more dominant smells and flavors rather than to thinking based on an emergent framework. For example, interviewed students who predicted that the smell of the product from the reaction of a substance A that smells of lavender and a substance B that smells of cinnamon would be lavender-cinnamon, despite the larger number of atoms of type A than of type B in the final product, often considered the relative number of atoms in their reasoning but argued that both smells could be sensed because the cinnamon smell was stronger than the lavender smell:

Smell of lavender is still a very light scent; cinnamon has a very strong scent, but you are using more lavender than cinnamon, mmm? It is possible that things are just in equilibrium, so that you could smell both [pause] I would choose lavender-cinnamon. (GCI4)

Further analysis of this student’s reasoning showed that he was using the term “equilibrium” to refer to a sort of “balance of forces” between few particles with a dominant scent and a larger number of particles with a weaker smell.

In the case of the reaction between reactants with sweet and acid taste, the influence of personal experience and beliefs on interview participants was even more dramatic, with many students suggesting that the product would taste sweeter than acidic because of the larger number of “sweet” atoms, but arguing that the acid taste could still be sensed (80% of GCI and 30% of GCII interviewees).

Students who applied an emergent framework in selecting an answer to this set of questions clearly recognized that the chemical reaction would affect the properties of the substance that is produced:

I think I would say a different color again [pause]. I don’t even think it’s even tempting to say it would have a bluish color just because there is more of the A that has the blue color. Because there is a reaction, I think that can definitively change things around. (GCII4; referring to question II in Table 1)

**Equal Ratio; Different Size**

The third set of questions in the sensory properties questionnaire was designed to explore whether students’ predictions were affected by the size of the atoms involved in the chemical reaction. In theory, one may expect that intuitive thinkers would consider both the number of atoms and their size as a measure of their influence on the properties of the final product. Results for question III in Table 1 for the prediction of the color of a product resulting from the combination of atoms with different sizes seem to confirm our hypothesis: 50.8% of the
students in the large sample ($N = 451$) selected the option in which the chemical product is expected to have the same color as the substance with the larger atoms (option “a”). However, this effect does not seem to influence students’ predictions to the same extent as the number of particles of a given component. Overall, it is important to point out that close to 90% of the students who answered this question selected an option that is consistent with the application of an additive heuristic (options “a” and “c”).

During the interviews, all of the students who selected options “a” or “c” (80% of GCI and 50% of GCII interviewees) referred to the size of the atoms during their explanations, but some of them were hesitant about the effect or influence of this variable on the properties of the chemical product. The following interview excerpts illustrate the types of reasoning followed by these participants:

Does the size like matters [pause]? Reddish is my guess [pause] red is probably going to stand out more than yellow. (GCI10)

I don’t know, is the bigger the size [pause]? does it mean like it’s stronger? but I am going to say it’s not [pause] so we have equal amounts and it’ll be an orange color. (GCII3)

The influence of particle size on student thinking seemed to be weaker for the predictions of the smell and taste of the chemical product as indicated by the results for questions III in Table 2 (option “a” was selected by 25.7%, $N = 451$ and 38.6%, $N = 451$ of the participants for the questions related to smell and taste, respectively). As was the case before, the analysis of interview transcripts suggests that personal beliefs about the strength of certain odors or flavors, or about personal ability to differentiate between smells or flavors may have played a central role in students’ choices. For example, in making predictions about the taste of the product of the reaction between a sweet substance (large atoms) and a sour substance (small atoms), several interviewees expected the atom size to influence the taste but indicated that sweet-sour (option “c”) was the likely outcome because sour was “stronger” than sweet. In the case of smell, several interview participants who selected option “c” mentioned their ability to “separate” smells:

I know smells are pretty common like, they kind of meld together, and you can definitively pick out different smells, like a dog, all these different smells it can smell [pause] so I think it would be a lemon-rose smell because the two products are together. (GCI1)

Students who applied an emergent framework in selecting their answers to this set of questions did not refer to the size of the particles as part of their responses.

**Reactants Without Perceptible Sensory Properties**

Students’ prediction for the likely properties of a product resulting from a reaction involving a reactant with no color, smell, or flavor followed very similar patterns to those already described. Analysis of the responses to question IV in Table 1 indicates that 85.1% of the participants ($N = 434$) in our large GCI sample expected the product of the 3:1 chemical combination of a substance with a dark blue color and another substance with no color to have a dark or a pale blue color. During the interviews, we realized that this question was interpreted in different ways by the participants. Some interviewees thought that the phrase “no color” meant that the substance was transparent, whereas others thought it meant that it was white. These different interpretations caused a few students to hesitate
between choosing option “a” (see Table 1), if they thought substance B was transparent, or “b,” if they thought this reactant was white. However, all of the participants who chose options “a” or “c” (70% of GCI and 50% of GCII interviewees) applied additive reasoning to make their predictions by considering that B atoms either would not affect the color of the product or would “dilute” it:

Dark blue color [pause] the no color is kind of clear and even though there is a lot of no colors around it, you kind of see through the no color the dark blue color, and doesn’t really change the dark blue color at all. (GCI9)

Pale blue [pause] it’s something like when you mix a color with water, it’s gonna dilute but still have some blue in it. (GCII6)

For this set of questions, students’ predictions for the smell or taste of the product of the chemical reaction exhibit very little difference to those for the color question. In these cases, more than 70% of GCI students who answered the sensory properties questionnaire (70.8% for smell, \(N = 434\); 82.6% for taste, \(N = 449\)) selected an option in which the product had similar properties to the reactant with scent or flavor (see questions IV in Table 2). Results from the interviews suggest that these students most likely used an additive framework to make their predictions, assuming that the substance with no smell or flavor either would not affect the properties of the product or would “dilute” the effect of the other reactant.

**Supplemental Studies**

The questions in our sensory properties questionnaire asked students to select the answer that represented the most likely properties of the product of a chemical reaction represented in particulate form. As with any research instrument that relies on a multiple-choice format and specialized representations of events or phenomena, the questionnaire has limitations that need to be acknowledged. For example, the multiple-choice format forces students to select the best possible answer and does not give them other options. In our case, all of the available responses required students to make their best prediction regarding the properties of the product of a reaction. It is possible that some students may have recognized that more information was required to make a prediction.

Likewise, it is possible that the particulate representations of matter used in the questionnaire may have misled some students. Research on alternative conceptions about the atomic nature of matter indicates that novice students tend to assume that the properties of atoms or molecules mirror those of the macroscopic substance (Ben-Zvi, Nylon, & Silberstein, 1987b; Nahkleh, 1992; Talanquer, 2006). Thus, although these types of images are regularly used in chemistry classes and all of the interviewees expressed familiarity with the types of representations used in the study, some students could have misinterpreted them. By convention, the circles or spheres used to represent the atoms that compose a molecule preserve their color and size before and after the reaction. Thus, these types of drawings may certainly strengthen the belief that the properties of atoms remain unchanged during a chemical process or that their properties mirror those of the macroscopic substances.

To test the validity and reliability of our results, we completed three additional studies in the spring of 2007 using modified versions of the sensory properties questionnaire. In the first study, the questionnaire was modified to avoid the potential problem of forcing some students to choose the most likely outcome of a reaction even when they may recognize that no definitive prediction can be made with the information provided. To test to what
degree this phenomenon may have affected students’ decisions, the correct multiple-choice option for all of the questions was changed from “the product has a different color, smell, or taste” to “more information is needed to make a prediction.” We also made sure that every question consistently had the same available options, that is, the product has (a) the properties of reactant A, (b) the properties of reactant B, (c) the properties of the mixture, (d) no sensible properties, and (e) more information is needed to make a prediction.

This modified version of the questionnaire was answered by 147 students enrolled in general chemistry I (section 1) at our institution. Overall, the results showed similar patterns to those described in the previous sections, with an average of over 90% of the students selecting responses consistent with the use of an additive framework. Although the difference in not significant ($t = 1.91, p > 0.05, df = 22$), the average percentage of students selecting the correct options decreased from 14.5% ($SD = 7.90$) in the original questionnaire to 9.28% ($SD = 5.11$) in the new version, possibly due to the fact that the modified correct option was not appealing to students who used an additive heuristic but who might have personal ideas about the dominance of one property over another. Given the similarity in the results, we decided to complete the other two supplemental studies using the modified version of the sensory properties questionnaire. This facilitated the analysis and comparison of all of the results collected in this final stage of our investigation.

In the second of our supplemental studies, the new version of the questionnaire was further modified by replacing three of the questions representing a chemical reaction by questions that illustrated the formation of simple mixtures. The goal was to evaluate whether there was a difference between responses involving mixtures or chemical reactions, and to provide positive examples in which an additive heuristic could be applied. This version of the questionnaire was completed by 102 students registered in a freshman natural science general education course. The analysis of our results revealed no significant difference between responses to the different types of questions. For example, an average of 4.99% ($SD = 2.70$) of the students selected the option “more information is required to make a prediction” in questions involving mixtures versus 5.08% ($SD = 2.93$) who selected this option in questions representing chemical reactions ($t = 0.05, p > 0.05, df = 10$). Specific answers to each of the different questions followed patterns very similar to those described in previous sections.

Finally, we built a third version of the sensory properties questionnaire in which chemical reactions were represented in symbolic form rather than particulate form. Images of particles such as that included in Figure 1 were replaced by chemical equations of the type $A + B \rightarrow AB$; reactions involving different particle ratios included cases such as $4A + B \rightarrow A_4B$, and $A + 2B_2 \rightarrow AB_4$. This version of the questionnaire was answered by 179 students enrolled in general chemistry I (section 2). Our analysis of the data shows that, on average, 20.2% ($SD = 3.91$) of the students selected the correct answer. This percentage is significantly higher ($t = 5.88, p < 0.05, df = 22$) than that obtained using the questionnaire based on particulate representations of matter, 9.28% ($SD = 5.11$), in a comparable general chemistry I section (section 1). This result suggests that conventional microscopic representations of chemical reactions may in fact be misleading for some students who do not clearly differentiate between the macroscopic and microscopic properties of matter. However, the results also indicate that the nature of the representation cannot be responsible for the choices made by the majority of the students. More than 70% of the participants in either the original study or these variations consistently selected answers that were indicative of the application of an additive framework independently of the type of representation. This is illustrated in Table 3 where we compare the responses to equivalent questions about color and taste (particulate vs. symbolic) given by students enrolled in comparable sections of general chemistry I (particulate, section 1; symbolic, section 2).
TABLE 3
Frequency of Responses for the Different Options Associated With Some of the Questions About Color and Taste in Modified Versions of the Sensory Properties Questionnaire Based on Microscopic and Symbolic Representations of Chemical Reactions [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

<table>
<thead>
<tr>
<th>Option</th>
<th>I, N = 147</th>
<th>II, N = 148</th>
<th>II, N = 175</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>COLOR</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blue → Yellow → Color?</td>
<td>1.36%</td>
<td>84.5%</td>
<td>48.6%</td>
</tr>
<tr>
<td>Blue + B → AB → Color?</td>
<td>2.33%</td>
<td>3.28%</td>
<td>2.86%</td>
</tr>
<tr>
<td><strong>TASTE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strong Salty → No Taste → Taste?</td>
<td>28.7%</td>
<td>35.2%</td>
<td>60.8%</td>
</tr>
<tr>
<td>A + B → AB → Taste?</td>
<td>35.2%</td>
<td>37.5%</td>
<td>20.2%</td>
</tr>
</tbody>
</table>

The acronym Min is used to refer to the option “More information is needed to make a prediction.”

GENERAL TRENDS AND IMPLICATIONS

Our results indicate that the majority of the students’ answers to the sensory properties questionnaire are consistent with the use of an additive framework in the prediction of the color, smell, and taste of the product of a chemical reaction. Support for this conclusion is drawn from a variety of data sources. For example, a significant proportion of the participants consistently selected those answers in which the properties of the chemical product corresponded to the linear combination of the properties of the reactants, taking into account the size and number of particles of a given type. The analysis of all questionnaires indicates that less than 3% of the students who participated in this study uniformly and systematically predicted that the properties of a chemical product may be expected to differ from those of the reactants. Even in these cases, it was common to find at least one answer that showed signs of the use of an additive framework as the basis for the prediction. These
results are rather surprising if we consider that most of the participants in this study were college students who had almost completed the first semester of a general chemistry course for science and engineering majors.

The analysis of the interview transcripts revealed that students who frequently selected the “additive” options (80% of GCI and 40% of GCII interviewees) seemed to conceive of chemical compounds as mixtures of substances that preserve some of their original properties in the final product. Thus, these students had not developed an emergent view of chemical properties. Results from the interviews also suggest that variations in the students’ predictions about smell and taste compared to those of color may be largely attributed to the influence of personal ideas about the relative strength of scents and flavors or a person’s ability to sense them, rather than to the meaningful understanding of the emergent nature of these properties. Many students seem to consistently use an additive framework to make predictions about the properties of the product, but they also apply some sort of “dominance principle” in which those flavors or odors perceived as more dominant determine the actual outcome. Similar commonsense ideas about dominance have been described by previous authors in the context of analyzing students’ alternative conceptions about forces and motion (Halloun & Hestenes, 1985) and genetics (Allchin, 2005; Donovan, 1997).

Our results suggest that the transition from additive to emergent reasoning in the prediction of the properties of the product of a chemical reaction may occur rather abruptly. This conclusion is based on the relatively small number of students who we identified as being in a “transitional” state. Of the 18 interviewed students, 11 of them (eight GCI and three GCII interviewees) applied an additive framework whereas five of them (one GCI and four GCII interviewees) systematically applied an emergent framework in making all of their predictions. Only two of the interviewees (one GCI and one GCII) seemed to be in “transition,” struggling to accommodate their personal beliefs and scientific understanding. These were the only two students who seemed to employ both types of reasoning, additive or emergent, from one question to another.

Responses from the students in “transition” reveal the difficulties that students may face in shifting from intuitive ways of thinking (additive framework) to scientific reasoning (emergent framework). Although these students were somewhat inconsistent in their predictions, the interviews clearly show that the variations in their responses were due less to commonsense reasoning about “dominant” properties than to the ill-defined nature of their understanding about chemical reaction and chemical models. In contrast with those students who almost without hesitation made predictions based on an additive heuristic, transitional students struggled when choosing an answer and were able to recognize the elements of the representations that seemed to misguide or confuse them. Consider the following excerpts from one of these students’ interview transcript:

Well, it’s confusing me ‘cause like in the other pictures when you see more of something you automatically assume that is what is going to override that, you know. But it is not always like that, because, you know, it could be doing with chemicals and who knows how they react, so depends on how you look at it. . . . My automatic assumption you know, when you see more of something then that’s what you see of, you know, when there is more color that is the one that you see, but it is not always gonna be the blue and black circles. It’s different with chemicals bonding and stuff like that, so I don’t know. I guess I should stick with “different” cause I don’t know what will react in this case. (GCI7)

Oh, again, I guess is kind of just how it’s drawn, you know. You see the bigger circle, the small circle, or a lot of little circles and one big circle, so it’s like, I don’t know, it’s the drawings that [inaudible], but I will go again with the “different” taste. (GCII7)

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Results from our supplemental studies indicate that the nature of the representation (particulate versus symbolic) used to depict the chemical processes had a small influence on students’ predictions of the properties of the product. Students were more likely to select an answer consistent with the application of an additive framework when the reactions were depicted in a particulate form. The use of colored atoms, which preserve their colors during the chemical process, may reinforce the idea that sensory properties are preserved during the transformation. However, our results using chemical equations represented in symbolic form showed that the nature of the representation did not have a significant impact on the answers of the majority of the participants.

One may also argue that the results of our study are due to the students’ lack of understanding of the interactions and processes that are responsible for the color, smell, and taste of a chemical compound. In fact, we know that all of these processes involve complex mechanisms that are not completely understood. However, it is precisely the limited familiarity with these processes that makes them ideal for exploring students’ intuitive ideas. In the absence of this specialized prior knowledge, most students applied an additive heuristic to build their predictions and were unable to transfer their limited knowledge about chemical properties and processes to other contexts. It is also true that the atomic or molecular representations used in this study were certainly simplistic compared to those of actual substances that exhibit sensible properties such as color, smell, and taste. It might be possible that some students with more advanced knowledge about how color, smell, and taste are sensed might have been confused by our overly simplistic representations. However, we did not find any evidence during our interviews that suggests that this type of confusion had a significant impact on the participants’ responses. None of the interviewees who demonstrated some background knowledge in the area showed any problem understanding the hypothetical nature of the questions or identifying the most plausible option.

Our study illustrates the pervasive nature of commonsense reasoning in chemistry students and reveals serious deficiencies in their preparation. Intuitive thinking seems to lead many students to conceive of physical and chemical properties as additive rather than emergent properties, similar to the way they tend to misclassify emergent processes as direct processes (Chi, 2005). As reported by previous authors (Ben-Zvi et al., 1987a; Boo & Watson, 2001), our work indicates that a large proportion of chemistry students conceive chemical reactions as additive rather than interactive, and that traditional courses in the discipline have little effect on these ideas. Jacobson and Wilensky (2006), Penner (2000), and Wilensky and Resnick (1999) have suggested that students’ difficulties with the concept of emergence are closely related to their failure to distinguish between micro- and macrolevels of analysis, their tendency to ascribe causal primacy to the macrolevel of the system, and their implicit assumptions about linear cause–effect relationships (i.e., large changes at the macrolevel require large changes at the microlevel). The results of our study support these conclusions but also reveal the strong influence of additive thinking on students’ reasoning about a system’s properties and behaviors.

Helping students recognize the existence of emergent properties in chemical systems is crucial if we want them to develop meaningful understandings of a variety of topics, from the atomic and molecular properties of individual particles to the behavior of many-particle systems (states of matter). In fact, the concept of “emergence” is becoming increasingly important as modern chemistry becomes more interested in physical and biological systems that exhibit self-organization (e.g., protein structure and function, membrane formation, etc.). The growing interest in understanding these types of complex systems, from a single cell to the human body, poses unique challenges to science students and teachers given the high-cognitive demands associated with the analysis of their structure and behavior.
(Hmelo-Silver & Azevedo, 2006). To support learning and teaching in this area, more research is needed to better understand how students’ reasoning about physical and chemical properties progress from reliance on additive to emergent frameworks. The present work is a first step in that direction.

For many years, chemical educators have argued that commonsense reasoning plays a minor role in the development of students’ misconceptions in chemistry given the abstract nature of many chemistry concepts (atoms, molecules, acids, oxidizing agents) (Taber, 2001). However, our research indicates that students’ empirical assumptions about the natural world and their simplistic reasoning heuristics seem to undergird many of their alternative conceptions (Talanquer, 2006). In particular, this study reveals that the concept of “emergence” is not trivial and that intuitive thinking may limit students’ ability to transfer their knowledge to different contexts. If students hold essentialist views about certain properties, such as color or smell, they may think that these properties are intrinsic to atoms or elements and thus should be present in their molecules or compounds. Changing these ideas will require more than mere explanations or exposure to chemical reactions in which the properties of the products differ from those of the reactants. The task will require the intentional design of learning opportunities for students to recognize and differentiate additive and emergent properties in a variety of contexts and to critically reflect on the relationship between molecular structure and observable properties.

REFERENCES


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