Chemical Education Research

Identifying Alternative Conceptions of Chemical Kinetics among Secondary School and Undergraduate Students in Turkey

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Introduction and Rationale for the Study

A constructivist view of science learning highlights the importance of recognizing and taking into account the ideas and meanings that learners construct from their daily lives or through formal instruction (1, 2). As Ausubel (ref 3, p 18) puts it: "The most important single factor influencing learning is what the learner already knows; ascertain this and teach him accordingly." Science educators have become increasingly aware of the importance of students' (preinstructional) conceptions of natural phenomena and events. Hence, the conceptions held by children, adolescents, and adults concerning a wide range of areas including chemistry have been extensively examined and documented by researchers over the past years (2, 4−14). Research on students' conceptions in various science domains and on how these conceptions change as a result of teaching (6, 7) has attempted to answer questions such as which alternative conceptions occur, what are their sources, how extensive are they, why are they so resistant to change, and what can be done about them? These studies have been largely interpreted within the constructivist learning paradigm (1, 2), and with the rise of that paradigm, teaching and learning have come to be seen as more domain-specific (5). Many science educators have modeled learning as a process of conceptual change or conceptual development (15, 16). When students are introduced, in school or elsewhere, to the scientific view of concepts, they start to organize and structure their own knowledge and actively construct new meaning by using their present conceptual frameworks to interpret new information in ways that make sense to them (1). Mortimer (17) argues that it would be oversimplifying to say that the new concept replaces an earlier one. Learners may have different ways of talking, thinking, and representing the material world, and accordingly, the new concept does not necessarily replace previous ones; rather, learners make choices to use them in contextually appropriate ways (18). In this respect, progression in learning is seen as changes in existing modes of thinking and having an understanding of scientific modes of thinking and talking (10, 17).

Research has revealed that secondary school (19) and undergraduate (8, 9, 20) students' understanding of chemical change is very poor. Specifically, students have difficulties in making links between the concrete level of chemistry (i.e., observable changes in substances) and abstract aspects of chemistry that explains observable changes in terms of various theories and models (2, 10). Johnson (20) claims that the underlying problem for students' lack of understanding in chemical change is located with the specification of the chemistry curriculum. He argues that the curriculum does not directly specify the key ideas that students need to have and develop to understand chemical change. For instance, he points out that the idea of a "substance", which is fundamental to the development of understanding in chemical change, is not explicitly mentioned in the English national curriculum. By not fully and appropriately understanding fundamental concepts and key ideas, many students have trouble with understanding the more advanced concepts that build upon these fundamental concepts and ideas (11).

Chemical reaction rates and the factors that affect them constitute an important area of the chemistry curriculum (12). Because of its importance in the understanding of reaction process, chemical kinetics is included in both secondary school and university curriculum in most countries (21). Given the importance of chemical kinetics and the diverse nature of the concepts and relationships that comprise it, students' conceptions of chemical kinetics have not been the subject of much research, especially at the university level (10, 13, 21). Nonetheless, chemical kinetics is considered as a difficult concept for both secondary school and undergraduate students to understand (2, 12, 13, 21, 22). Accordingly, this study was intended to provide empirical evidence about secondary school and undergraduate students' conceptions of chemical kinetics. The key assumption behind this study is that teachers and curriculum developers' awareness of the students' point of view would aid in designing teaching activities that overcome students' alternative conceptions in this field and match the curriculum to the needs of students. Bearing these points in mind, this study addresses the following research question: "What are Turkish secondary school and undergraduate students' alternative conceptions of chemical kinetics?" In this paper, the term "alternative conceptions" is used to describe ideas students develop before or after teaching on a particular scientific topic that differ significantly from socially agreed on concepts of the scientific community (2).

Methodology

Sample Demographics

In Turkey, chemical kinetics is first introduced in the curriculum in upper secondary school. The topic is taught again in detail in the first-year and third-year of a five-year preservice chemistry teacher-training program. The sample for the main study included 108 upper secondary school students (SS) (ages 15−16) in three classes from two schools, 48 university first-year students (UF), and 35 university third-year students (UT). A

subsample of the students (10 SS, 7 UF, 7 UT) was also interviewed in order to investigate their understanding in more depth and to check for appropriate interpretation of the written responses. Data were collected after formal classroom teaching in chemical kinetics. Secondary school students were selected from two different schools in a town located in northern Turkey. Schools and classes were selected to represent a mixture of socioeconomic areas and to cover a wide profile of students. Students in the university had about average performance in the Student Selection Examination *(23)*.

Data Collection

The main data collection instrument had 11 open-ended diagnostic questions and was used in conjunction with individual interviews with a number of students. An example of these questions is shown in Figure 1; all of the diagnostic questions are provided in the supporting material. The questions investigated two related yet different types of understanding in chemical kinetics: expressing scientific knowledge (e.g., recalling facts, concepts, methods, and processes) and using this knowledge in different contexts. Driver and Erickson *(24)* claimed that students might develop scientific knowledge as a result of instruction and other experiences; however, they do not necessarily relate these to actual phenomena. For that reason, the diagnostic questions targeted both students' scientific knowledge about the topic and how they apply this knowledge in a novel situation. The questions were designed to allow investigation of students' conceptions in different contexts; therefore, any key scientific idea in chemical kinetics was addressed through more than one question *(25)*.

We could not find suitable diagnostic questions to use in the study from among the small number of studies that have previously been carried out in this field. As a result, we designed most of the questions in the diagnostic tests. The questions were first piloted with 20 secondary school and university students and the further piloting conducted with 95 students both in secondary school and university in Turkey. This led to modification of the questions in response to confusions and problems identified.

Data Analysis

A coding scheme was developed by reviewing students' responses in interviews and to written questions and by identifying common ideas and ways of explanation. Students' responses to the diagnostic questions were categorized into three groups: responses including alternative conceptions about the topic; responses including scientifically acceptable conceptions about the topic; and all other responses. The category "all other responses" is allocated for incomprehensible responses or cases where no response is given. Each of these three categories was further classified under different subcategories. The alternative conceptions identified for over 10% of the students in any educational level are reported here. The researcher gave some training to a fellow Ph.D. student so as to test the inter-rater reliability of the coding scheme. Accordingly, 10% of the sample responses to two questions were coded by two independent coders and over 90% reliability was achieved.
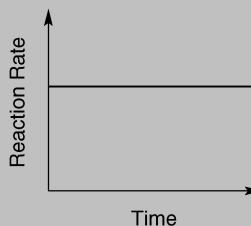
Results and Discussion of Alternative Conceptions

Analysis of the data yielded 11 common alternative conceptions (see Table 1). As presented below, in many instances,
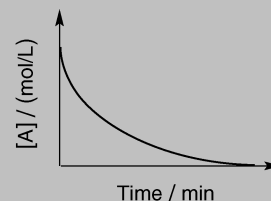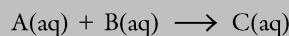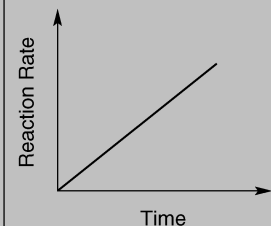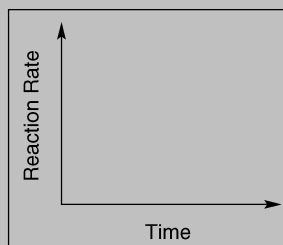
Figure 1. Reaction rate and time questions for eliciting students' responses.

similar alternative conceptions were found among secondary school and undergraduate students.

Defining Reaction Rate as Reaction Time

When students were asked to define the notion of reaction rate, around 33, 29, and 3% of SS, UF, and UT students, respectively, believed that reaction rate is the period of time taken for a reaction to occur. As quoted below, students could not differentiate between "reaction rate" and "reaction time". While under certain conditions reaction time is a constant quantity for a reaction, the rate of a reaction is

Table 1. Distribution of Students' Common Alternative Conceptions Regarding Chemical Kinetics

Alternative Conceptions Identified	Number and Frequency (in %) of Responses, by Student Category		
	Secondary School $N = 108$	University First-Year $N = 48$	University Third-Year $N = 35$
Defining reaction rate as reaction time	35 (32.4)	14 (29.2)	1 (2.9)
Difficulties explaining how reaction rate changes as the reaction progresses: The rate of a reaction increases with time	65 (60.1)	26 (54.2)	25 (71.5)
A rise in temperature does not affect the rate of exothermic reactions	5 (4.6)	6 (12.5)	3 (8.6)
An increase in temperature decreases exothermic reactions rates	6 (5.5)	27 (56.3)	10 (28.6)
Exothermic reactions occur faster than endothermic reactions	34 (31.4)	12 (25)	13 (37.1)
Endothermic reactions occur faster than exothermic reactions	16 (14.8)	9 (18.8)	3 (8.6)
Activation energy is the kinetic energy of reactant molecules	17 (15.7)	4 (8.3)	
Activation energy is the (total) amount of energy released in a reaction	23 (21.3)	5 (10.4)	
A catalyst increases the yield of products	25 (23.1)	4 (8.3)	12 (34.3)
A catalyst does not affect or does not change the mechanisms of a reaction	60 (55.5)	38 (79.1)	21 (60)
An increase in the initial concentration of reactants would increase/ decrease the rate of a zero-order reaction	71 (65.7)	24 (50)	11 (31.4)

dynamic during the reaction. A secondary school student stated that:

> Substances react to form a new substance. Reaction rate is the time required for a reaction to be completed.

Chemical kinetics is concerned with the rate of reactions, which is a way of understanding how fast or how slow a reaction occurs. From a student's intuitive viewpoint, it might be logical to relate reaction rate to reaction time (also discussed below).

Difficulties Explaining How Reaction Rate Changes as the Reaction Progresses

The reaction rate—time question (see Figure 1) asked students to describe, both graphically and textually, how the reaction rate changes with time. The results indicated that a majority of students' responses for each educational level included alternative conceptions.

The idea that "reaction rate increases as the reaction progresses" (23, 13, and 3% of SS, UF, and UT, respectively), "reaction rate is constant" (19, 6, and 6% of SS, UF, and UT, respectively), "reaction rate increases up to a maximum value, and remains constant at this value" (8, 25, and 54% of SS, UF, and UT, respectively), or "the reaction rate increases up to a maximum value and from this level decreases gradually to zero when the limiting reactant is consumed" (2, 10, and 9% of SS, UF, and UT, respectively) were quite common among both secondary school and undergraduate students. Many students had difficulties in understanding that the reaction had the highest rate at the beginning of the reaction and the lowest rate at the end: rather they tended to think the opposite. The student responses and corresponding graph in Figure 2 illustrate this alternative conception.

Those students' understanding might be constrained by the perceptual experiences from their daily lives (e.g., a wood fire burns slowly at the beginning and goes faster thereafter) or from the chemistry laboratory (2). For instance, the alternative conception mentioned above could have arisen from the observation in a chemistry laboratory that during the reaction of magnesium with dilute acid, it usually takes some seconds for the surface oxide layer to dissolve before the surface of the metal is exposed to

A

B
The concentration of A [reactant] is decreasing, which means the rate of reaction would increase. [SS]

Reaction rate = d/dt, [where d is the product] while the concentration of product increases with time; the rate of the reaction will increase. [UF]
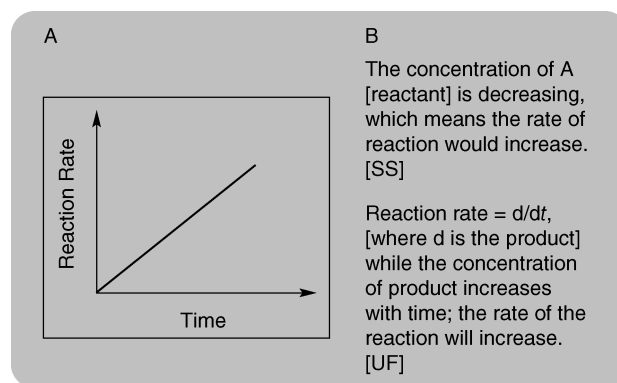
Figure 2. (A) One of the graphs drawn in response to part A of the question in Figure 1. (B) Explanations of this graph for the question in Figure 1, part B, from a secondary school student (SS) and from a university first-year student (UF).

the dilute acid. Students may have thought that because these reactions are exothermic the system supplies energy as heat to the surroundings, and as a result, the reaction speeds up. Another reason for students' alternative conceptions could be that the approach used in the secondary school textbooks emphasized the initial and final state of a reaction, overlooking the dynamic nature of the reaction system (25). The rate of a reaction is commonly expressed in three different forms: (i) the initial rate of a reaction; (ii) the instantaneous rate of a reaction; and (iii) the average rate of a reaction over a time interval. The results revealed that though both school and undergraduate students were more likely to give a correct answer to how a change in the initial reaction conditions (e.g. increasing concentration, increasing the surface area, or using a catalyst) would influence the reaction rate, yet these students had alternative conceptions about how reaction rate changes as a reaction progresses. One of the reasons might be that when comparing two different reactions rates, students are comparing the *average rate* or comparing *reaction time* of these reactions. However, in the other case, students need to appreciate the notion of *instantaneous rate*, which is

conceptually demanding. Another reason could be that such concerns have little place in the curriculum. The secondary school textbook (26) included the idea that the average rate of a reaction over a time interval can be calculated by dividing the change in concentration over that time period by the time interval but did not include sufficient information about the notion of instantaneous rate. The idea that the instantaneous rate can be determined from a tangent line at the relevant instant of time on a graph of concentration versus time was emphasized at the university level. Students' understanding of the notion of reaction rate and an appreciation of differences among "the initial rate", "the instantaneous rate", and "the average rate over the chosen time interval" are essential for understanding the dynamic nature of reaction system and other related concepts in kinetics (10). During teaching, differences among these terms and concepts need to be acknowledged and the teacher should monitor whether students understand the differences among these concepts.

A Rise in Temperature Does Not Affect the Rate of Exothermic Reactions

A number of students (5, 13, and 9% of SS, UF, and UT, respectively) argued that the rate of an exothermic reaction would not be affected by an increase in temperature. However, it should be noted that most of those students believed that a rise in temperature would increase the rate of endothermic reactions. Here is an example from a university first-year student:

> Since the reaction gives out heat, a rise in temperature would not affect the reaction rate. However, if a reaction took heat [from its surroundings]; the reaction rate would increase with temperature. Because a rise in temperature increases the rate of a reaction that takes in heat.

The underlying idea behind this response was probably that exothermic reactions release energy; therefore, they do not need energy to proceed and a rise in temperature would not affect the reaction rate. Students seemed to confuse the chemical kinetic concepts with the thermodynamic concepts. Indeed, there is considerable evidence to show that students believe that endothermic reactions could not be spontaneous; however, exothermic reactions could be spontaneous (8, 27).

An Increase in Temperature Decreases the Rate of Exothermic Reactions

A high percentage of students, mainly UF (6, 56, and 29% of SS, UF, and UT, respectively), argued that when the initial temperature was increased, the rate of exothermic reactions would decrease, but the rate of endothermic reactions would increase with an increase in temperature. This alternative conception mostly arose because students tried to interpret the reaction rate and extent of the reaction by using Le Châtelier's principle and thus confused the concept of reaction rate and chemical equilibrium (2). The following quote from a university first-year student illustrates this view:

> Since the reaction is an exothermic reaction, an increase in temperature would affect opposite side and it decreases the reaction rate. The reaction gives out heat; therefore a rise in temperature would decrease the reaction rate.

The results revealed that the students had misapplied Le Châtelier's principle and they were not aware of the limitations on the use of the principle (cf. refs 2 and 28). This alternative

conception was also found in studies in chemical equilibria (2, 29) and thermodynamics (8, 28). In an attempt to overcome this difficulty, various suggestions have been made. For example, Le Châtelier's principle has been considered inappropriate for teaching in schools and elementary courses except as a historical treatment (30).

Exothermic Reactions Occur Faster than Endothermic Reactions

Around 31, 25, and perhaps surprisingly, 37% of SS, UF, and UT, respectively, claimed that (at the same initial temperature) exothermic reactions occur faster than endothermic reactions. The most common reasoning was that exothermic reactions release or give off energy and occur spontaneously and faster, but endothermic reactions require energy to proceed; therefore, endothermic reactions cannot be spontaneous (cf. refs 8, 11, and 27). Here is an example from a university third-year student:

> The first reaction [the exothermic reaction] occurs faster, because exothermic reactions do not require energy [to proceed], they occur spontaneously. However, endothermic reactions need a certain amount of energy to progress; therefore, an endothermic reaction cannot occur spontaneously.

Students argue that exothermic reactions have to be spontaneous. They seem to confuse the rate of a reaction with the spontaneous occurrence of a reaction. A study by Ribeiro et al. (31) revealed that students often use the everyday notion of the word spontaneous; thus, the word spontaneity is related to observable features such that a chemical reaction is spontaneous if it is observable. Their findings also revealed that students have a view that a chemical reaction is spontaneous if no intervention is needed. The majority of students in their sample correctly explained that $\Delta G < 0$ is the criterion for spontaneity. Ribeiro et al. claim (31) that the main source of this alternative conception is everyday use of the words. Therefore, teachers need to make the differences between the social language of school science and the social language that students bring to the classroom (31). During teaching, it should also be pointed out that the rate of a reaction is the concern of kinetics, while enthalpy and Gibbs free energy changes are the subject of thermodynamics.

Endothermic Reactions Occur Faster than Exothermic Reactions

Several students (15, 19, and 9% of SS, UF, and UT, respectively) argued that endothermic reactions occur faster than exothermic reactions. The most common reasoning was that endothermic reactions take energy from their surroundings, but in exothermic reactions energy is given out; therefore, endothermic reactions occur faster than exothermic reactions. As one of the university first-year students put it:

> [E]ndothermic reactions occur faster. Endothermic reactions take heat from the surroundings.... Since an increase in temperature raises reaction rate, the second reaction [endothermic reaction] occurs faster.

The student seems to think that endothermic reactions absorb heat energy from their surroundings; therefore, they have got more heat energy than exothermic reactions. Thus, the student concludes that the endothermic reaction occurs faster than the exothermic reaction.

Activation Energy Is the Kinetic Energy of Reactant Molecules

Students' understanding of the concept of activation energy and their ability to relate it to reaction rates were the focus of a diagnostic question called "activation energy". Students were asked whether they could compare rates of two different chemical reactions based on the reactions' activation energy values. On several occasions, students, mainly secondary school students, showed confusion between activation energy and overall enthalpy changes. A number of students (16 and 8% of SS and UF, respectively) defined activation energy as the kinetic energy of reactant molecules. Many of those who viewed activation energy as the kinetic energy of reactant molecules reached a conclusion that the bigger the activation energy is, the faster a reaction occurs. Here is an example from a university first-year student:

> Activation energy is the energy of reactant molecules. In other words, due to movement, reactant molecules have a certain amount of kinetic energy. E_a [Activation energy] is the energy of those molecules. ...The second reaction occurs faster, because it has a higher activation energy. An increase in E_a (in other words an increase in kinetic energy of molecules) increases collisions and increases the number of molecules that overcome the energy barrier. As a result the reaction rate rises.

Although this student's response includes some ideas of chemical kinetics (i.e., referring to theories of kinetics), the student could not use those ideas properly. One of the reasons might be that he or she could have learned or been taught the concept by rote. It is important to note that the kinetic energy of reacting molecules might be equal to the activation energy of the reaction. A reaction occurs if the collision has enough energy to be either equal or greater than the activation energy and if the orientation of the collisions allows for correct bond formation. Students, however, seem to confuse these ideas. This might originate in the teacher's comments during teaching the concept of activation energy.

Activation Energy Is the Amount of Energy Released by a Reaction

Some secondary school and university first-year students (21 and 10%, respectively) defined activation energy as the amount of energy released by a reaction. Here is an example from a secondary school student:

> Activation energy is the energy released after a reaction. ...The second reaction [with a higher E_a] is faster, because more energy is released. The faster a reaction is, the more energy is released.

When this student's explanation to another question (called the "enthalpy question") is examined, it appeared that she had a general idea that exothermic reactions occur faster than endothermic reactions. Here is her explanation to the "enthalpy question":

> I think the first reaction [the exothermic reaction] occurs faster, because exothermic reactions give out heat, but endothermic reactions take in heat. Of course, giving heat out is easier; therefore, those reactions [exothermic reactions] occur faster.

At the secondary school and university levels, the concept of activation energy is mainly presented at the symbolic level (i.e., drawing upon an energy profile diagram) and also the particulate level (i.e., referring to the transition-state theory). That approach requires students to make links between particulate and mathematical modeling (10). Nevertheless, the results revealed that a few secondary school students had difficulties in interpreting an energy profile diagram for a reaction and associating it with theoretical models. Such students interpreted the diagram based on surface features of the diagram; for example, they simply stated that "activation energy is the highest point on the diagram" or "activation energy is the peak of the energy profile diagram". It appears that more attention should be given to the interpretation of symbolic representations of the concept and its relationships with the particulate level. Activation energy is one of the fundamental ideas in chemical kinetics and the study results suggest that activation energy is poorly understood by secondary school students.

A Catalyst Increases the Yield of Products

A number of students (23, 8, and 34% of SS, UF, and UT, respectively) believed that a catalyst would increase the yield of the products (cf. ref 28). The majority of their justifications are well represented in this quote:

> The yield of the product would increase, because a catalyst provides an alternative reaction path with reduced activation energy. Therefore, more molecules would pass through the energy barrier and as a result more products would be formed.

As pointed out earlier, many students could not differentiate between reaction rate and reaction time. Therefore, it is likely that students thought about this situation in terms of time. That is, they may think that adding a catalyst will result in more products in the same time frame than an uncatalyzed reaction. If this is the case, the student statement above is not wrong but the inference about the yield is wrong. Research in other areas of chemistry, for instance, in chemical equilibrium (2) suggest that students do not anticipate that a catalyst lowers both the forward and reverse activation energies; rather they believe that a catalyst just reduces the forward activation energy and as a result students may reach the conclusion that the catalyst favors the yield of the product. That might be one of the reasons for students' commitments to alternative conceptions about the effect of catalyst on the yield of product.

A Catalyst Does Not Affect or Change the Mechanism of a Reaction

While most of the students were aware that an appropriate catalyst increases the reaction rate by lowering the activation energy of the reaction, the majority of those had limited knowledge about how an appropriate catalyst affects the mechanisms of the reaction and how it works. Indeed, several students (56, 79, and 60% of SS, UF, and UT, respectively) stated that the catalyst would not affect or change the mechanisms of the reaction. The following quotation from a university first-year student illustrates this perception:

> A catalyst will not change the reaction step, because it does not react with the reactants during the reaction. If an uncatalyzed reaction occurs in two steps, with a catalyst it also occurs in two steps.

It was surprising to see that the majority of the UF students (79%) and around two-thirds of the UT students had alternative conceptions about the mechanism of a catalyzed reaction.

Although 18, 10, and 34% of SS, UF, and UT students, respectively, argued that a catalyst would change the mechanism of a reaction, most of them did not provide further explanation for their answers. Only a few students, mainly undergraduates, suggested that catalyzed and uncatalyzed reactions have completely different mechanisms and that the catalyst reacts with one or more of the reactants and accordingly a series of reactions takes place, during which the catalyst is consumed and regenerated. As a result, such students concluded that a catalyzed reaction occurs in more than one step.

Increases in the Initial Concentration of Reactants Would Increase or Decrease the Rate of a Zero-Order Reaction

One of the diagnostic questions (the "nitrogen monoxide" question) asked students how an increase in the initial concentration of the reactant (NO) would affect the rate of the given reaction (the decomposition of nitrogen monoxide on a platinum surface). The question assessed students' competence in manipulating variables in a rate equation. A majority of the secondary school students (66%), half of the UF students, and around one-third of the UT students' responses included alternative conceptions about the relationships between the concentrations of reactants and the reaction rate. In many cases, the students attempted to answer the question based on a rate equation, but they had forgotten to consider some variables in the rate equation (i.e., the reaction order). A few students argued that a linear relationship exists between concentration of reactants and reaction rate; they did not anticipate the order of the reaction or the role of the solid catalyst. Accordingly, they expected a higher rate from increasing concentration of reactants. Indeed, the interviews showed that although the students were reminded that this reaction is zero order with respect to NO, most of them assumed that is a second-order reaction with respect to NO. Here is an example from an interview with a secondary school student:

> Researcher: How would an increase in the concentration of nitrogen monoxide affect this reaction rate?
> Student: When we increase the concentration of nitrogen monoxide, the reaction rate will increase. Increasing the concentration favors formation of products that will increase the rate of the reaction.
> Researcher: The rate increases?
> Student: Yes...
> Researcher: What about the order of the reaction? In that case it is zero order with respect to nitrogen monoxide. Does it matter whether it is a zero-order or first-order reaction?
> Student: No...
> Researcher: Are you saying that increasing the concentration of reactants increases the reaction rate whether it is a zero-order or a first-order reaction?
> Student: Yes.

Such students had a general view that the concentrations of reactants in the rate equation have exponents equal to the stoichiometric coefficients of the reactants in the balanced equation for the reaction. This reasoning works only if the reaction occurs in one step: namely, elementary reactions. The students were not aware that the relation between rate and concentration and the order of a reaction must be determined experimentally. These facts deserve attention during teaching.

Conclusion and Educational Implications

This study provides insights into students' understandings of chemical kinetics. The results indicate that secondary school and undergraduate students possess generally low levels of conceptual understanding of chemical kinetics, even though this topic had been presented many times. Several alternative conceptions exhibited by secondary school students persisted among undergraduates, indicating the persistence of such alternative conceptions. Many prospective chemistry teachers seem to start their professions with limited conceptual understanding of the key scientific ideas in chemical kinetics. The results suggest that a substantial review of teaching strategies is needed. In particular, decisions relating to planning and teaching require teachers to consider the nature of the alternative conceptions presented in this paper. A number of examples were noted in this study in which students inappropriately attributed a relationship between thermodynamic and kinetic factors and tried to use thermodynamic ideas to explain the kinetic of a reaction: in some cases, they confused the concept of reaction rate and chemical equilibria. For instance, a highly significant number of secondary school and undergraduate students (nearly half of the whole sample) argued that "exothermic reactions occur faster" or that "endothermic reactions occur faster". Surprisingly, the proportion did not change much from secondary school to university. These results are striking in that half of the prospective chemistry teachers had alternative conceptions about some fundamental concepts in thermodynamics and kinetics. It is intuitively plausible that they will pass those alternative conceptions on to their students.

Thermodynamics is about how stable things are in one state versus another; in contrast, kinetics is about how quickly or slowly species react and is about the progress of a chemical reaction. From a student's intuitive viewpoint, it is possible to confuse thermodynamic quantities like Gibbs free energy with kinetics ones like activation energy. One of the reasons could be that these concepts were often taught separately (e.g., some concepts in kinetics and thermodynamics such as activation energy, enthalpy, spontaneity, entropy, free energy, the notion of exothermic and endothermic reactions) and links between those concepts were not specified or were ignored in the curriculum, as observed by Viennot *(32)* in other contexts. Thus, students failed to move between several concepts. Without being explicitly introduced to the relationships between some concepts in kinetics and thermodynamics, students would have conceptual difficulties in moving between them. As argued earlier, students also had similar conceptual difficulties in some concepts of kinetics and chemical equilibria. For instance, a great number of students, particularly university first-year students, drew upon Le Châtelier's principle and argued that "an increase in temperature decreases exothermic reactions rates". It seems that the students confused equilibrium with kinetic concepts or they simply misunderstood Le Châtelier's principle. These findings are supported by studies in chemical equilibrium *(2, 28)* that reveal that students regularly misapply Le Châtelier's principle in cases where its scope is limited. Therefore, during teaching, limitations on the use of Le Châtelier's principle should be clearly addressed. Understanding chemical kinetics requires an integrated conceptual understanding of some fundamental ideas: the particulate nature of matter, the kinetic molecular theory, and dynamic aspects of chemical reactions

(21, 33). Therefore, it would be useful to treat closely related concepts of chemistry together. In other words, during instruction the teacher and the curriculum should help students to move back and forth in order to make links or specify differences between different concepts introduced to them through teaching.

Acknowledgment

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Supporting Information Available

Diagnostic questions used in this study. This material is available via the Internet at http://pubs.acs.org.