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Designing and evaluating an evidence-informed instruction in chemical kinetics

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We have investigated the effects of a teaching intervention based on evidence from educational theories and research data, on students' ideas in chemical kinetics. A quasi-experimental design was used to compare the outcomes for the intervention. The subjects of the study were 83 university first-year students, who were in two different classes in a 4-year pre-service science teacher-training programme in Turkey. During teaching, an 'evidence-informed instruction' was applied in the experimental group whereas 'traditional instruction' was followed in the control group. Students' understandings of chemical kinetics were elicited through a series of written tasks and individual interviews. The results showed that while there was no significant difference in students' understandings in chemical kinetics in the two groups on the pre-test, in the post-test the students in the experimental group achieved significantly higher learning gains in chemical kinetics than did the students in the control group. Moreover, in response to teaching, students in the experimental group were more likely to use their knowledge consistently across different contexts (average 63.1%) than students in the control group (average 19%). The significance of these findings for further research, and for policy and practice relating to science teaching, are discussed.

Keywords: catalysis, chemical kinetics, rate of reaction, alternative conception, research evidence informed practice, research evidence based practice

Introduction

The ideas held by children, adolescents, and adults concerning a wide range of areas, including chemistry, have been extensively examined by researchers over the past years (Duit, 2009). It is quite understandable why students' ideas concerning chemical phenomena have become a research focus, since literature in this field has indicated that many students at school and university level, struggle to learn chemistry and many do not succeed (Nakhleh, 1992). School (Andersson, 1986; Watson *et al*., 1997; Ahtee and Varjola, 1998; Van Driel *et al*. 1998; Boo and Watson, 2001) and undergraduate (Sozbilir and Bennett, 2006) students' understanding of chemical change has been the subject of much research in recent years. Overwhelmingly, studies have revealed that students' understanding of chemical change is very poor–even amongst those who have successfully passed public examinations (Johnson, 2000).

Chemical reaction rates and the factors that affect them constitute an important area of the chemistry curriculum (Cachapuz and Maskill, 1987). As Atkins and Jones (1999, p.594) put it *"chemical kinetics gives us insights into how chemical reactions take place at an atomic level, so it brings us to the heart of chemistry."* Theories of kinetics (*e.g*. the collision theory and the transition-state theory) are fundamental ideas, because those theories give insight into how a chemical reaction occurs, based on kinetics and thermodynamics. Understanding of how to control a reaction rate is very important in a range of areas from fundamental research to industrial processes. Due to its importance in the understanding of reaction processes, chemical kinetics is included in both school and university curriculum in most countries (Cachapuz and Maskill, 1987; Justi, 2002). There is some empirical data available on students' difficulties in learning chemical kinetics (De Vos and Verdonk, 1986; Cachapuz and Maskill, 1987; Justi, 2002; Lynch, 1997; Van Driel, 2002; Cakmakci *et al*., 2006; Cakmakci, 2010a). Students' ideas about chemical kinetics were often quoted in the studies focusing on chemical equilibrium (Hackling and Garnett, 1985; Quilez and Solaz, 1995; Van Driel *et al*., 1998; Van Driel and Gräber, 2002) and thermodynamics (Johnstone *et al*., 1977; Sozbilir, 2001; Goedhart and Kaper, 2002; Sozbilir and Bennett, 2006). Research on learning difficulties associated with chemical kinetics is investigated and documented by some researchers (Cachapuz and Maskill, 1987; Lynch, 1997; Van Driel, 2002; Justi, 2002; Cakmakci, 2010a). The results showed that chemical kinetics was considered as a difficult concept to understand by both school and undergraduate students (Justi, 2002; Cakmakci, 2010a).

In our previous studies, we investigated Turkish school and undergraduate students' ideas about chemical kinetics (Cakmakci, 2005; Cakmakci *et al*., 2006; Cakmakci, 2010a) and our results showed that several alternative conceptions exhibited by school students persisted amongst

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Table 1 Students' common conceptual difficulties and alternative conceptions related to chemical kinetics: 'Evidence' from research data

Conceptual difficulty/alternative conception identified	**Data source**	**Revealed by**
Inability to define the rate of reaction (*e.g.* defining reaction rate as reaction time)	High school students and undergraduates (Turkey)	Cakmakci (2005; 2010a)
Difficulties in explaining how reaction rate changes as the reaction progresses	High school students and undergraduates (Turkey)	Cakmakci et al. (2006)
Difficulties in explaining chemical phenomena based on theoretical models	High school (England)	Cachapuz and Maskill (1987)
An increase in the initial temperature does not affect the rate of exothermic reactions	High school students and undergraduates (Turkey)	Cakmakci (2010a)
An increase in initial temperature of the system decreases exothermic reactions rate	High school students and undergraduates (Turkey)	Cakmakci (2010a)
An increase in initial temperature of the system decreases the reaction rate: collisions of fast moving particles would be less effective, because the particles would bounce back.	High school students (The Netherlands)	Van Driel (2002)
Applying Le Châtelier's principle while answering questions related to rates of reactions	Undergraduates and chemistry teachers (Spain)	Quilez and Solaz (1995)
An increase in initial temperature of the system can decrease the rate of the forward reaction and increase that of the reverse one	High school students (Australia)	Hackling and Garnett (1985)
Exothermic reactions occur faster than endothermic reactions	Undergraduates (Turkey)	Sozbilir (2001)
Endothermic reactions occur faster than exothermic reactions	Undergraduates (Turkey)	Sozbilir (2001)
Confuse the rate of a reaction with the spontaneous occurrence of a reaction	Undergraduates (Turkey)	Sozbilir (2001)
Activation energy is the kinetic energy of reactant molecules	High school students and undergraduates (Turkey)	Cakmakci (2010a)
Activation energy is the (total) amount of energy released in a reaction	High school students and undergraduates (Turkey)	Cakmakci (2010a)
A catalyst increases the yield of products	High school students (Australia)	Hackling and Garnett (1985)
A catalyst can affect the rates of forward and reverse reactions differently	High school students (Australia)	Hackling and Garnett (1985)
A catalyst does not affect or does not change the mechanisms of a reaction	High school students and undergraduates (Turkey)	Cakmakci (2010a)
An increase in the initial concentration of reactants would increase/decrease the rate of a zero order reaction	High school students and undergraduates (Turkey)	Cakmakci (2010a)
Having conceptual difficulties in interpreting empirical data and graphical representation	High school students and undergraduates (Turkey)	Cakmakci et al. (2006)

undergraduates (Cakmakci, 2010a; see also Table 1). Therefore, an alternative approach for teaching chemical kinetics is desirable. Recently, evidence-informed instruction (EiI) has been used for improvement in the teaching of specific pieces of knowledge, skills or values (Millar *et al*., 2006; Bridges *et al*., 2009).

Theoretical foundations: evidence-informed practice

The importance of research evidence in shaping and enhancing educational policy and practice has been acknowledged by several researchers (*e.g.,* Davies, 1999; Gilbert *et al*., 2002; Aikenhead, 2005; Millar *et al*., 2006; Bridges *et al*., 2009). Hargreaves (1997) argued that effective teaching should be guided by research, and educational research should have much more relevance for the practice of teachers than it has at present. As he put it:

> *Practising doctors and teachers are applied professionals, practical people making interventions in the lives of their clients in order to promote worthwhile ends - health or learning. Doctors and teachers are similar in that they make decisions involving complex judgements. Many doctors draw upon research about the effects of their practice to inform and improve their decisions; most teachers do not, and this is a difference. Educational research could and should generate a better equivalent for teachers; reducing the difference would enhance the quality of teachers' decision-making.* (Hargreaves, 1997, p.406)

From its origins in research in clinical medicine and health care, an evidence-based practice has become increasingly influential in education (Thomas and Pring, 2004; Millar *et al.*, 2006; Bridges *et al.*, 2009). Recently, systematic reviews on what works best in classroom practice and evidence-informed practice and policy have become a focus of interest in many countries (Aikenhead, 2005; Bridges *et al.*, 2009). For instance, a systematic review process favoured by the UK government started to offer some good examples of research on changing policy and practice (The Evidence for Policy and Practice Information and Co-ordinating Centre (EPPI-Centre): http://www.eppi.ioe.ac.uk). The underlying ideas behind this are to make reliable research findings accessible to the people who need them, whether they are making policy, practice or personal decisions, and to ensure that professionals and policymakers have constantly updated access to the findings of good quality research (Hood, 2003).

Millar *et al.* (2006) made a distinction between the terms 'research evidence-informed' and 'research evidence-based' practice. On the one hand, evidence-informed practice is about the extent to which the design of a teaching intervention is influenced by research findings or ideas; on the other hand, evidence-based practice is about the extent to which research has provided evidence about the outcomes of the intervention, and hence provided a justification for teaching something in one way rather than another (Millar *et al.*, 2006, pp. 10-11). The evidence-based practice movement (Bridges *et al.*, 2009) has helped curriculum developers and educational practitioners focus on how research can lead to improvement in the teaching of specific pieces of knowledge or skills that we value. Various research evidence-informed instructional approaches have been used by many researchers; for example, the framework of ‘developmental research’ (Lijnse, 1995); the model of ‘educational reconstruction’ (Duit *et al.*, 1997), the model of ‘design-based research’ (Design-Based Research Collective, 2003; Collins *et al.*, 2004) and the design of teaching based on the notion of ‘learning demands’ (Leach and Scott, 2002). These approaches have some distinctive features (Ruthven *et al.*, 2009); however, as presented below they also share some common features. For instance, great attention is given to:

1. the clarification of the science subject matter structure (i.e. an analysis of the particular content to be taught),
2. students’ conceptions about the domain (*e.g.* empirical investigation of students’ conceptions and/or reviewing literature in this field), and
3. making links between insights from research, and the development of instruction.

Drawing upon these premises, a teaching intervention can be developed in other areas of science from the same viewpoints (Komorek and Duit, 2004); for instance, in chemical kinetics where students have difficulties to understand (Justi, 2002; Cakmakci, 2010a). Now, there is convincing evidence to show that it is possible to improve students’ learning against specified curriculum goals when the design of a teaching intervention is informed by evidence from educational theory and research data (Andersson and Bach, 2005; Leach *et al.*, 2006; Millar *et al.*, 2006).

Research aims and significance of the study

There is considerable evidence to show that changes in the science education a student receives can stimulate a positive effect on students’ understanding of science (Leach *et al.*, 2006); however, there is not much research of this kind (Gilbert *et al.*, 2002; Duit, 2009). What is largely missing from the literature is how the design of a teaching facilitates students’ understanding of chemical kinetics (Justi, 2002; Duit, 2009). Bearing these points in mind, this study aims to investigate the effects of a teaching intervention, the design of which is informed by evidence from educational theories (Leach and Scott 2002; Mortimer and Scott, 2003) and research data, on students’ ideas about chemical kinetics (Justi, 2002; Cakmakci *et al.*, 2006; Cakmakci, 2009; 2010a; also see Table 1). Accordingly, the aim of the study is addressed through the following research question:

> *How effective is our evidence-informed instruction (EiI) in facilitating students’ understanding of chemical kinetics when compared to the traditional instruction?*

Our work has been influenced by a number of researchers who have argued that developing effective teaching interventions and curriculum development is essentially research activities (Lijnse, 1995; Duit *et al.*, 1997; Leach *et al.*, 2006) because effective teaching involves having an understanding of key issues underpin the nature of effective teaching in particular domains (*e.g.* addressing how and why certain activities lead to learning, and what factors influence their effectiveness).

Design and methodology

Research design and participants

A quasi-experimental design with a non-equivalent pre-test-post-test control group was used to compare the outcomes for the intervention. The subjects of the study were 83 first-year university students (47 in the experimental group and 36 in the control group) (ages 18-19), who were in two different classes in a 4-year pre-service science teacher-training programme in Turkey. Two modes of treatment were used in this study. Students in the experimental group (EG) were instructed by using an evidence-informed instruction (explained later), whereas students in a similar group, the control group (CG), was exposed the university’s normal programme of teaching. Both classes had been taught by the same teacher. The teacher first taught chemical kinetics concepts to the control group and then taught to the experimental group in following weeks. The intention was to reduce influences of the intervention on the teacher’s regular teaching.

Context and intervention

The study was undertaken over a two-week period (four class hours per week) during which the topics related to chemical kinetics were covered in the *General Chemistry-II* course as a part of the regular curriculum. Students’ responses to the pre-test showed that before the intervention, there was not a significant difference between these two classes in terms of their understandings of chemical kinetics ($p > 0.05$). Therefore, one of the classes was randomly selected as the experimental group. Both groups were instructed in an equal amount of instructional time. Both in the control and experimental groups, concepts of chemical kinetics were taught in the same order (explained later). In order not to influence the teacher’s regular teaching, nothing was said to the teacher about the intervention while he was teaching chemical kinetics to the control group in the way he usually taught it. After the teacher completed teaching chemical kinetics to the CG, the rationale for the EiI and certain features of the EiI (*e.g.* students’ common conceptual difficulties in chemical kinetics, their possible sources, what can be done about them, differences between teacher-centred and student-centred teaching, different kinds of classroom communications; features of the talk between the teacher and students, *etc.*) were made clear to the teacher, and teaching materials (*i.e.* a Power Point presentation, worksheets for group works, *etc.*) were presented to him. The teacher was instructed to teach chemical kinetics to the EG by considering these issues. After the first week of the EiI, a reflection on the teaching and further discussions about the EiI were also held with the teacher.

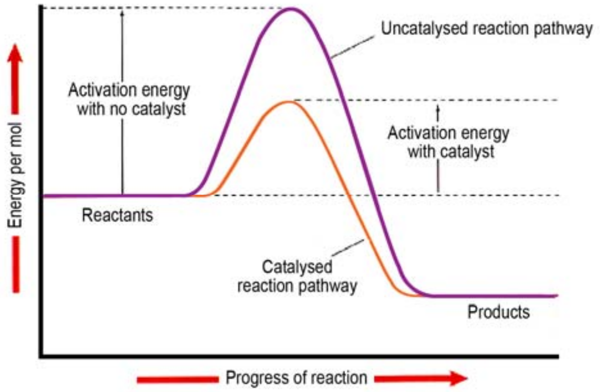


Fig. 1 An energy profile for a catalysed and uncatalysed reaction

Development of evidence-informed instruction

In the experimental group, an evidence-informed instruction (EiI) on chemical kinetics was developed with the aim to help students to properly understand chemical kinetics concepts. Three distinct but related perspectives informed the design of the EiI on chemical kinetics. These perspectives do not follow strictly upon one another but mutually influence each other.

The first component contained a detailed content analysis of the domain and the Turkish chemistry curriculum so as to identify the key scientific ideas in chemical kinetics, to explore the types of explanations that have been provided in the textbooks, to explore the ways in which the explanations are related to the scientific explanations, and to specify their limitations (Cakmakci, 2005; Cakmakci, 2009). In order to check the validity of this conceptual analysis, the identified key ideas and conceptual and propositional knowledge statements that are necessary for students to fully understand chemical kinetics were discussed with five chemistry professors. As a result, the key ideas and statements were modified accordingly. These key ideas and statements are available in Cakmakci (2005, pp. 255-258).

The second component included a review of the literature on teaching and learning about chemical kinetics and identifying common students' difficulties in this field (Hackling and Garnett, 1985; Justi, 2002; Cakmakci, 2005; 2010a; Cakmakci *et al.*, 2006; see also Table 1).

Bearing these points in mind, the third component included specifying teaching goals for chemical kinetics, and considering teaching approaches and tools in order to achieve these goals. In a broader sense, drawing upon a social constructivist view of learning (Leach and Scott, 2002) and communicative strategies for teaching (Mortimer and Scott, 2003), an EiI was designed to support students' understandings of chemical kinetics.

Implementation of the evidence-informed instruction

In order to clarify the designed teaching intervention and implementation of this intervention, it is worth illustrating it on a particular idea in chemical kinetics, for instance, on the notion of catalysis. The components of the teaching intervention, presented below, are interconnected in some levels, but they do not follow strictly upon one another.

(1) The clarification of science subject matter structure In chemistry textbooks, the effect of a catalyst on reaction rates is usually mentioned on the diagram shown in Fig. 1 (Atkinson and Hibbert, 2000, p.109; Chang, 2005, p.567). However, such diagrams do not depict the most important feature of catalysed reactions, that catalysed reactions involve sequences of several activated complexes and intermediates (Haim, 1989; Cakmakci, 2009). Such diagrams, which are not intended to describe the mechanism of a reaction, can give students the impression that the catalysed and uncatalysed reactions proceed via the same mechanism (a one-step mechanism). These diagrams might be one of the reasons for students' lack of knowledge and for their commitments to scientifically incorrect arguments about the notion of catalysis (Cakmakci, 2005) (see Table 3: questions 10f and g). Drawing upon the results of our previous studies, we have proposed an alternative way of explanation for teaching the notion of catalysis (see Fig. 2).

It is claimed that much of the meaning-making in science classrooms is achieved not only through talk (by teacher and students) but also through various images, and visual representations (Kress *et al.*, 2002). Understanding and making links between different forms of explanations play a crucial role in teaching and learning scientific concepts. Accordingly, by attempting to provide a more comprehensible approach for teaching the concept of (homogenous) catalysis, it would be more fruitful to teach the role of a catalyst in reaction mechanisms on the diagram shown in Fig. 2, by making clear that a catalyst is a substance that works by changing the mechanism of the reaction in that it actually reacts with the one or more of the reactants/products to form a new intermediate (Cakmakci, 2009). The figure with the reaction mechanisms, which is presented in Fig. 2, can help students to understand the role of catalysts in chemical reactions. Writing a catalyst in the chemical equation could help students to understand that a catalyst enters into the reaction; however, at the end of the reaction it is recovered unchanged. Links between different forms of explanations are made more explicit during teaching, and explanations containing characteristics that can be problematic for proper understanding of the concept of catalysis are taken into account (Kim and Van Dusen, 1998).

(2) Identifying students' conceptions about the domain and (3) making links between insights from research, and the development of instruction Curriculum specifications typically provide information at a macro level about what is to be taught. However, it would be better to move from unclear and ambiguous 'general goals' towards 'content specific goals' and to design teaching accordingly (Leach and Scott, 2002). Thus, these content specific goals can provide a much more fine-grained analysis of learning points that need to be addressed by teacher. In this respect, specifying teaching goals can be informed by research

Depletion of the Ozone Layer

Ozone (O_3) is present in the ozone layer in the stratosphere and provides protection against biologically destructive, short wave-length ultraviolet radiation from the sun. Higher levels of radiation resulting from the depletion of the ozone layer have been linked with increases in skin cancers and cataracts. Mario J. Molina and F. Sherwood Rowland (1974) discovered that the depletion of ozone in the stratosphere partly results from the Chlorine-catalysed decomposition of O_3, and it is for this work that in 1995 they shared the Nobel Prize in Chemistry. Chlorine atoms in the stratosphere originate from the decomposition of chlorofluorocarbons (CFCs), such as $CClF_3$ and CCl_2F_2 amongst other sources. At one time, CFCs were used widely as refrigerants, solvents for degreasing, spray-can propellants, and blowing agents for making plastic foams. Usage of CFCs is banned in many nations; in fact, its use is spreading to Third World countries, such as the nations of Africa and many in South America, and its availability has a profound effect on their economies.

Equations for the corresponding elementary reaction (**without a catalyst**):

$O_{3(g)} + O\bullet_{(g)} \longrightarrow 2\,O_{2(g)}$ Ea= 17.1 kJ/mol

Equations for the corresponding elementary reaction (**with a catalyst**; Cl• (atomic chlorine radical) is the catalyst for this reaction).
The mechanism can be divided into two steps:

Step 1: Cl• reacts with ozone to form ClO • and O_2

$Cl\bullet_{(g)} + O_{3(g)} \longrightarrow ClO\bullet_{(g)} + O_{2(g)}$ Ea= 2.1 kJ/mol

Step 2: ClO• reacts with O• to produce Cl• and O_2

$ClO\bullet_{(g)} + O\bullet_{(g)} \longrightarrow Cl\bullet_{(g)} + O_{2(g)}$ Ea= 0.4 kJ/mol

Overall: $O_{3(g)} + O\bullet_{(g)} \xrightarrow[Cl\bullet]{} 2\,O_{2(g)}$ Ea= 2.1 kJ/mol

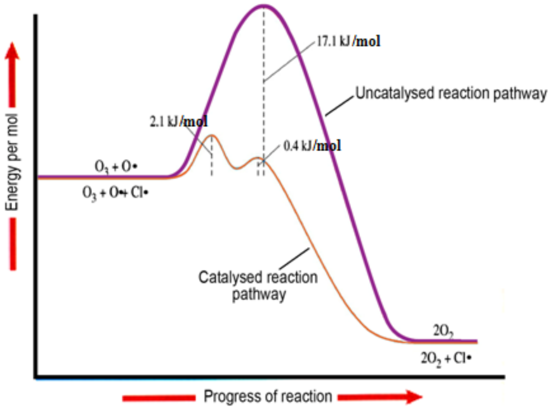


Fig. 2 Different kinds of explanation about the action of a homogeneous catalyst.

evidence. In other words, students' common difficulties in this field, such as the alternative conceptions reported in the literature (see Table 1), should be taken into account. For the concept of catalysis, content specific teaching goals include:

To *open up students' own ideas* about catalysts and catalysis.

To *emphasise* the idea that:

- enzymes and catalysts are important for industry and for our daily lives;
- a catalyst is a substance that could be a solid, liquid or a gas.

To *build on* the ideas that:

- a reaction occurs if the collision has enough energy to be either equal to or greater than the activation energy, and if the orientation of the collisions allows for bond formation;
- a catalyst accelerates a reaction by altering the mechanism so that the activation energy is lowered.

To *draw attention to,* and to *emphasise*, the ideas that:

- a catalyst is a substance that works by changing the mechanism of the reaction;
- the reaction rate may depend on the amount of catalyst – on its concentration–for homogenous catalysis, or depend on its surface area for heterogeneous catalysis;
- when catalysts and reactants are in the same phase, the reaction proceeds through an intermediate species;
- in reversible reactions a catalyst reduces both forward and reverse activation energies equally; as a result it speeds up both forward and reverse reactions and cannot increase the final equilibrium yield, but it gets to the final equilibrium state faster.

To *introduce, and support the development of*, the idea:

- that the principles of the catalysis process can be used to explain the effect of enzymes on reaction rates.

To *draw attention* to:

- mechanisms of a catalysed reaction and uncatalysed reaction. A proposed mechanism can never be proven to be correct. It can only be consistent with all available data

- the nature, scope and limitations of models (*e.g.* teachers should be aware of the limitations of models that they introduce to students) and the relationships between different forms of explanations.

To *teach*;

- students how to reason in a coherent way, and to show them the limits of each level of explanation.

Having identified specific teaching goals and students' common conceptual difficulties in this field (*e.g.* students believe that a catalyst does not affect or does not change the mechanisms of a reaction, see Table 1), it is then necessary to consider teaching approaches that might be used to address those goals. We therefore considered some strategies that have been proposed in the literature for teaching for conceptual understanding (mentioned below).

The teaching intervention on catalysis took one class hour and it included following key features. At the beginning of the lesson, Döbereiner's (1780-1849) reaction of hydrogen with oxygen on a platinum catalyst and his discovery of catalysis were mentioned and (i) the teacher elicited students' existing knowledge about catalysts and the process of catalysis by asking: How does a catalyst increase the rate of a reaction? Students' responses were not judged as correct or wrong; rather their different ideas were made explicit. Through this discussion, it became clear that although most of the students were aware that an appropriate catalyst increases the rate of a reaction by reducing the activation energy, the majority had limited knowledge about the process of catalysis. Following this discussion, a short video clip of an experiment about the catalysed decomposition of hydrogen peroxide in the presence of potassium iodide was shown to the students, and possible equations for this reaction without and with the catalyst were written. It was emphasised that from those equations the catalysed reaction occurs in 'two steps', but according to the 'one-step' energy profile diagram for catalysis, which was taught at upper secondary level, the catalysed reaction occurs in 'one-step' (see Fig. 1). Students were asked whether these two forms of explanations are consistent with each other, and if not, whether this is a problem. The aim of this activity was (ii) to make the apparent implausibility of the scientific views explicit to the students. The teacher helped students to recognise the limitations and inconsistencies of their existing knowledge and the scientific views. With that discussion, students faced with anomalies that create dissatisfaction in the existing ideas and thereby have the necessity for new ideas (Strike and Posner, 1992). Following the discussion, (iii) a new scientific view, the more-than-one-step representation of transition states was introduced to students. The aim of the activity was to make the new scientific view appear intelligible and plausible (Strike and Posner, 1992). The role of teacher was to convince students of the reasonableness of the scientific view. It was also made clear why the wrong ideas were wrong. Knowing why the wrong idea is wrong is as important as knowing why the right idea is right (Palmer, 2003). (iv) In order to support students in making sense of and internalising the new scientific view, the depletion of ozone layer in the stratosphere by chlorine atoms was illustrated to the students (see Fig. 2). That required students to make links between different kinds of explanation (*e.g.* between the symbolic and sub-microscopic levels); therefore the role of the teacher as a mediator was crucial. Critically, this role involved helping students to relate different forms of explanations (see Fig. 2) and challenging students to think about the phenomenon in terms of the new scientific viewpoint. It was also made explicit that the principles of catalysis process can be used to explain the effect of enzymes on reaction rates. This activity aimed (v) to reinforce participants' understanding of the ideas presented, and to provide them with opportunities to consolidate and enhance their knowledge about catalysis. Those activities seemed to help students to contrast their own ideas against those of their classmates, the scientist's and the teacher's, and to address a specific teaching goal (Mortimer and Scott, 2003).

In general, the teacher appeared to understand the rationale of the designed EiI and implemented it as planned. However, analysis of the video recordings suggests that the dialog between the teacher and students could have been improved by training the teacher how to handle socio-scientific issues/dilemmas (*e.g.* usage of CFCs in underdeveloped countries) and how to enhance the quality of argumentation in the classroom.

The nature of the traditional instruction

Since nothing was said to the teacher about the intervention study, the teacher taught chemical kinetics to the control group in the way he usually does. On the basis of the video recordings, it appeared that the teacher used lecturing, questioning, note taking, and drill and practice instructional strategies in teaching chemical kinetics in the control group. Generally, the teacher lectured to the students, and they were asked to take notes. Teaching involved the teacher in imparting information, typically by way of dictating notes to the class. Exercises on the worksheets were practised in the classroom, and the teacher answered students' questions and made suggestions if needed. Since the teacher mostly lectured to the students, the approach used in the control group was named as the 'traditional instruction'. The teacher suggested to students to follow any general chemistry textbook that they wanted. Both in the control and in the experimental groups, concepts of chemical kinetics were taught in the following order: the rate of a chemical reaction, measuring reaction rates, effect of concentration on reaction rates: the rate law, zero-order reactions, first-order reactions, second-order reactions, theoretical models for chemical kinetics: collision theory and activated-complex theory, the effect of temperature on reaction rates, reaction mechanisms, and catalysis (Petrucci *et al.*, 2001). It should be pointed out that, in the control group the teacher explained the effect of catalyst on reaction rates based on Fig. 1 and on the Maxwell-Boltzmann energy distribution diagram.

Table 2 The content and focus of questions (Cakmakci, 2010b)

Question	Description of question	Aims to test the same ideas*
1	Solutions in different quantities, but with a same concentration of reactants, were placed in two containers and students were asked to explain in which set of conditions the reaction would occur faster. They were also asked to justify their answers.	♣
2	The question presented students with a graph that shows how the concentration of a reactant changes with time. Students had to assess the data and describe how the reaction rate changes with time.	#
3	The same amounts of chemical species were placed in two differently shaped containers, and students were asked to explain in which set of conditions the reaction would occur faster. They were also asked to justify their answers.	♣
4a	The question presented students with a graph that shows how the concentration of a reactant changes with time. Students had to justify how the data supports the scientists' conclusion about the reaction order. They were also asked to justify their answers.	@
4b	The second part of question 4 asked how the rate of this zero-order reaction changes with time. They were also asked to justify their answers.	#
5	The question was adopted from the study by Sozbilir (2001), and aimed to probe students' understanding of the concepts of activation energy and enthalpy.	□
6	The question was adopted from the study by Andersson (1986), and aimed to elicit students' understanding of the effect of temperature on reaction rates. Students were asked to explain whether the outside of a hot water pipe or a cold water pipe would rust more after a period of time.	Δ
7	The question aimed to explore how students understand the notion of rate law and the variables in a rate equation.	β
8	The second part of question 8 asked students to explain how an increase in the initial temperature of the system would affect the rate of the given reaction.	Δ
9	The question presented students with written data that show how the concentration of a product changes with time. Students had to assess the data and find out how the reaction rate changes with time.	#
10	The question included some statements about the effect of catalyst on reaction rates, the rate constant, the yield of products, activation energy, enthalpy, and the mechanisms of the reaction. Students were asked to explain whether these statements are correct or wrong.	&

Notes: * Symbols indicate that the same basic ideas were tested in these questions.

Data collection and instruments

Data were collected through three different instruments. Data sources include questionnaires, interviews and video recording of classroom activities. Video recording was not the main data collection method. Rather it was used as a supplementary; it was used to gather data from the classroom about teaching the concepts of chemical kinetics. In this paper, we present no systematic analysis of this data.

The Chemical Kinetics Concepts Achievement Test (hereafter termed CKCAT)

Based on a conceptual analysis of the domain, key scientific ideas in chemical kinetics were identified and a number of diagnostic questions were devised to provide contexts through which students' understanding about each of the key scientific ideas could be investigated. A diagnostic test (CKCAT) consisting of 10 questions was used to probe students' conceptual understandings of chemical kinetics. The focus of each question is outlined in Table 2 and all questions can be accessed in Cakmakci (2010b). The majority of these questions were previously used and validated in our previous studies (Cakmakci, 2005; Cakmakci *et al.*, 2006; Cakmakci, 2010a). The diagnostic questions investigated two related but different types of understandings in chemical kinetics. These are the ability to express scientific knowledge (*e.g.* recalling facts, concepts, methods, and processes) and to use this knowledge to generate explanations in different contexts (*e.g.* in formal or everyday settings). The diagnostic questions were in two parts; the first part involves making a prediction of some kind, and this is followed by an opportunity for students to explain their prediction. The CKCAT was administered to the experimental and the control groups after the teaching of kinetics has been completed. Before the intervention, five of these questions in the CKCAT (Q1-Q5-Q7-Q8 and Q10) were administered as a pre-test to investigate students' pre-conceptions of chemical kinetics, and to make a comparison between those two groups. The pre-test was conducted to the CG and EG in the same week; however, the post-test was taken by CG and EG students at different times. Data (post-test) were collected one week after students had been taught chemical kinetics. In other words, the interval between the teaching and the assessment (post-test) for both groups was the same.

Interviews

A subsample of the students (n = 15) (Pre-test = 3 students in the experimental group; Post-test = 5 students in the control group and 7 students in the experimental group) was interviewed in order to probe their understanding in more depth, and to check for appropriate interpretation of the written responses. This subsample was chosen to represent the diversity in responses to the written questions. Interviews took place on a one-to-one basis and were audio-recorded. During the interviews the participants were provided with their pre- or post-instruction questionnaires and asked to justify their responses. If necessary, follow-up questions were used to clarify participants' responses and further probe their ideas.

Video recording of classroom activities

In order to investigate what actually went on in the classrooms, both classes were video-recorded during the study (eight class hours in total). That allowed us to identify

Table 3 Percentage of students' answers for the diagnostic questions (Pre-test) (N=74)

	Answer chosen as %						
Question	(A)	(B)	(C)	(D)	(E)	(F)	other or no answer
1	36.5	47.3*	16.2				0
5	20.3	32.4	13.5	33.8*			0
7	70.3	2.7	5.4	20.2*			1.4
8	8.1	43.2	23.0*	5.4	5.4	14.9	0
10a	3.6	81.9*	14.5				0
10b	89.2*	10.8	0				0
10c	67.5	15.7*	16.9				0
10d	37.3*	43.4	19.3				0
10e	66.3*	16.9	16.9				0
10f	32.5*	39.8	27.7				0
10g	36.1	30.2*	33.7				0
10h	65.1*	15.7	19.3				0

Notes: * Symbol shows the percentage of correct answer to the question.

the nature of teaching in each classroom and to analyse a number of different dialogs between the teacher and students and among the students. However, this is not the focus of this paper.

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 categorised into three groups: 'responses including scientifically incorrect ideas about the topic', 'responses including scientifically accepted ideas about the topic', and 'all other responses'. The category 'all other responses' is allocated for incomprehensible responses or cases where no response is given. As mentioned earlier, the diagnostic questions were in two parts, therefore, both parts were considered together for the analysis. For instance, if a student gave a correct answer for the first part, but gave an incorrect explanation for the second part of the question, it was judged that this student's response includes scientifically incorrect ideas about the topic. In order to increase reliability, students' responses were separately coded by two authors and inconsistencies found were reconsidered and resolved.

Limitations of the study

It is important to acknowledge that in this study, an evidence-informed instruction is implemented in only one classroom and the findings are quite promising. Studies that clarify whether the evidence-informed instructions are applicable to the other countries chemistry curricula would be beneficial.

In this study, a limited number of comparisons were made in order to investigate how students use their ideas across different contexts. That was done, because one way to explore understanding about a concept is to look at the consistency of individual students' responses to several questions probing understanding of the same idea. Whether the nature of students' ideas about reaction rate is a theory like, fragmented structure or in the form of multiple frameworks (Taber, 2000) is beyond the scope of this present study. However, it would be interesting to investigate the nature of students' ideas in a way Taber (2000), among others, did.

Results

Students' understandings of chemical kinetics prior to teaching

Before the intervention, five of the questions in the CKCAT (Q1-Q5-Q7-Q8 and Q10) were administered as a pre-test to investigate students' pre-conceptions of chemical kinetics and to make a comparison between two groups. Mean score (out of 40) of the pre-test for the control group was 16.58 (SD=7.11) and for the experimental group was 13.57 (SD=6.92). This difference was tested using an independent-sample *t*-test, and the results showed that there was not a significant difference between these two groups in terms of their previous knowledge about chemical kinetics (t (72) = 1.84, $p > 0.05$). Thus, it was assumed that students in the experimental group could be compared to other students in the control group (see Tables 3 and 4).

The results of the pre-test showed that the majority of the students had limited knowledge about the notion of reaction rates (see Tables 3-4). For instance, while most of the students were aware that an appropriate catalyst increases the reaction rate by lowering the activation energy of the reaction (see Table 3: questions 10a, b and e), the majority of those had limited knowledge about how an appropriate catalyst affects the mechanisms of the reaction and how it works (see Table 3: questions 10c, f and g). In addition, they had difficulties in providing theoretical explanations about the dynamic nature of reactions. Several students gave explanations based upon taken-for-granted everyday knowledge that were often tautologous – generally unacceptable or insufficient mode of explanation in science. Here is an example:

> *It is not possible to compare the rates of these reactions, because these are two different reactions.* [A student's response to Question 5].

In general, similar conceptual difficulties that were identified in the previous studies (Justi, 2002; Cakmakci, 2010a) were found from students' responses to the pre-test (see Tables 3-4). In many instances students confused the concepts of chemical kinetics with the concepts of chemical

Table 4 Percentage of students' responses to the diagnostic questions and summary of an independent-sample *t*-test (Pre-test) (Control Group, N=34; Experimental Group, N=40)

	Pre-test				
	Control Group (N=34)		Experimental Group (N=40)		
Questions	Correct response (%)	Incorrect response (%)	Correct response (%)	Incorrect response (%)	*t*-value
1	55.9	44.1	40.0	60.0	1.36*
5	47.1	52.9	27.5	72.5	1.75*
7	26.5	73.5	15.0	82.5 2.5 ¥	1.16*
8	20.6	79.4	25.0	75.0	-0.44*
10a-h (average)	57.4	42.6	60.0	40.0	-0.64*

Notes: * Not Significant at 0.05;
¥ shows all other categories; due to small number of responses, percentages of 'all other categories' (i.e. incomprehensible responses or cases where no response is given) are not presented as a separate column on the table.

equilibria (Hackling and Garnett, 1985; Quilez and Solaz,1995) and thermodynamics (Johnstone *et al.*, 1977; Sozbilir and Bennett, 2006). For instance, a student response to question 5 was as follows:

> *Since the reaction in the first vessel is exothermic, it occurs faster* [than the one in the second vessel]. *Because, it* [the exothermic reaction] *occurs spontaneously*. [However] *we need to give energy from outside to endothermic reactions. But, exothermic reactions do not require energy from outside* [to proceed], *they occur spontaneously.*

Students' responses to question 5 showed that 24% of the students stated 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. They seemed to link the rate of a reaction with the spontaneous occurrence of a reaction (Johnstone *et al*., 1977; Sozbilir and Bennett, 2006; Cakmakci, 2010a). They were not aware that $\Delta G<0$ is the criterion for spontaneity. Therefore, during teaching, the relationships and differences between some concepts in kinetics and thermodynamics (*e.g.*, activation energy, enthalpy, spontaneity, entropy, free energy, the notion of exothermic and endothermic reactions) were explicitly introduced to students in the experimental group. The results also suggested that students had similar conceptual difficulties in some concepts of kinetics and chemical equilibria. For instance, students tried to apply Le Châtelier's principle while answering questions related to rates of reactions and argued that 'an increase in initial temperature of the system decreases the rate of exothermic reactions' and 'an increase in initial temperature of the system can decrease the rate of the forward reaction and increase that of the reverse one' (Hackling and Garnett, 1985; Quilez and Solaz, 1995; Cakmakci, 2010a). Here is an illustrative quotation:

> *An increase in initial temperature of the reaction* [system] *will increase only the rate of reverse reaction. Since the reaction is an exothermic reaction, an increase in temperature would affect opposite side of the equilibrium. For that reason, the rate of reverse reaction will be increasing.* [A student's response to Question 8].

By considering such research evidence, during teaching, limitations on the use of Le Châtelier's principle were clearly addressed in the experimental group.

Changes of students' understanding of chemical kinetics in response to teaching

Table 5 presents the students' post-test answers to the diagnostic questions. The results of the post-test indicated that mean score (out of 88) of the post-test for the control group was 39.11 (SD=12.60) and for the experimental group was 71.38 (SD=13.15) (see Table 6). This difference was tested using an independent-sample *t*-test, and the results showed that students in the experimental group achieved significantly higher learning gains in chemical kinetics than students in the control group (t (81)= - 11.14, p <0.001) and in most cases these gains were statistically significant (see Table 6). As discussed earlier, an alternative approach for teaching the notion of catalysis is implemented in the experimental group (see Fig. 2). The results also indicated that students in the experimental group showed statistically significant improvements in the area of catalysis in response to teaching than students in the control group (t (81) = - 9.07, p <0.001) (see Table 6, Question 10). This result suggests that the EiI had a positive effect on students' understanding about the notion of catalysis.

A paired-sample *t*-test was used to determine whether there was any improvement in students' understandings from the pre-test to post-test within their classes. For this analysis, students' responses to five questions (Q1-Q5-Q7-Q8 and Q10) that were used in the pre- and post-test were used. The paired-sample *t*-test results indicated that students in the control group showed no significant improvement in their understanding in response to the traditional instruction (t (33) = -0.16, p >0.05), however students in the experimental group showed statistically significant improvements in response to the evidence-informed instruction (t (39) = - 12.56, p <0.001).

As presented above, the results indicated that a significant number of students in the control group did not make substantial progress following teaching. However, when the nature of students' explanations was examined, it appeared that some students improved their ability to articulate their claims. Prior to the instruction, students tended to justify their claims by simple examples, or by drawing upon taken-for-granted everyday knowledge, or by tautological restatements of available information in the tasks. An example of such an explanation to question 6 is:

> *The outside of the hot water pipe would get rustier than the outside of the cold water pipe. Because the hot water pipe is warmer.*

As is evident in this excerpt, the explanation is mainly about tautological restatements of available information in the question. By contrast, following teaching, students were more likely to use some forms of theoretical model, such as the notion of rate law, the concept of derivation or the rate

Table 5 Percentage of students' answers for the diagnostic questions (Post-test) (Control Group, N=36; Experimental Group, N=47)

Question	Answers chosen as %													
	A		B		C		D		E		F		other or no answer	
	Control	Experimental	Control	Experimental	Control	Experimental	Control	Experimental	Control	Experimental	Control	Experimental	Control	Experimental
1	27.8	29.8	55.6* 5.5**	70.2*	11.1	0							0	0
2	0	0	63.9* 2.8**	89.4*	5.6	4.3	19.4	4.3	8.3	2.1			0	0
3	8.3	6.4	77.8* 11.1**	91.5*	2.8	2.1							0	0
4a	8.3*	74.5* 2.1**	47.2	17	44.4	6.4							0	0
4b	0	2.1	72.2	23.4	2.8	2.1	19.4* 2.8**	72.3*	2.8	0			0	0
5	14.3	0	37.1	2.1	8.6	2.1	30.6* 9.4**	91.6* 4.2**					0	0
6	30.6	6.4	0	17	66.7* 2.7**	74.5* 2.1**							0	0
7	66.6	66	2.8	0	5.6	2.1	25*	31.9*					0	0
8	5.6	0	66.7	2.1	16.5* 2.8**	95.7*	2.8	0	5.6	0	0	2.1	0	0
9	2.8	8.5	27.8	14.9	5.6	4.3	36.1* 25**	70.2*	2.8	0			0	2.1
10a	0	2.1	100*	97.9*		0							0	0
10b	100*	100*	0	0		0							0	0
10c	69.4	23.4	25*	68.1*	0	0							5.6	8.5
10d	5.6*	93.6*	94.4	6.4		0							0	0
10e	83.3*	83*	13.9	17	0	0							2.8	0
10f	16.7*	89.4*	83.3	10.6	0	0							0	0
10g	80.6	10.6	16.7*	87.2*	0	0							2.8	2.1
10h	94.4*	95.2*	2.8	0	0	0							2.8	4.3

Notes: * Symbol shows the percentage of correct answer to the question; ** symbol shows the percentage of correct answer to the first part of the question but incorrect reasoning is given in the second part of the question

Table 6 Percentage of students' responses to the question in the chemical kinetics concepts achievement test (CKCAT) and summary of an independent-sample *t*-test

Question	Post-test				t-value
	Control Group (N=36)		Experimental Group (N=47)		
	Correct response (%)	Incorrect response (%)	Correct response (%)	Incorrect response (%)	
1	55.6	44.4	70.2	29.8	-1.37*
2	63.9	36.1	89.4	10.6	-2.89**
3	77.8	22.2	91.5	8.5	-1.77*
4a	8.3	91.7	74.5	25.5	-7.86***
4b	19.4	80.6	72.3	27.7	-5.54***
5	30.6	66.7	91.6	8.4	-7.36***
6	66.7	33.3	74.5	25.5	-0.77*
7	25.0	75.0	31.9	68.1	-0.68*
8	16.5	83.5	95.7	4.3	-12.22***
9	36.1	63.9	70.2	27.7 2.1¥	-3.25**
10a-h (average)	55.5	43.1 1.4¥	88.3	8.8 2.9¥	-9.07***

Notes: * Not Significant; ** Significant at $p<0.05$; *** Significant at $p<0.001$.
¥ shows all other categories; due to small number of responses, percentages of "all other categories" (i.e. incomprehensible responses or cases where no response is given) are not presented as a separate column on the table.

of change; nevertheless, most of the students in the control group could not use them appropriately in the questions. For instance, 92% of the students in the control group had limited knowledge about the notion of the rate of change, and incorrectly expressed a rate equation related to question 4a. It ought to be stressed that one of the reasons for students' wrong conclusions occurs as a result of misapplications of some rules, formulae, principles or variables that are embodied in the task. The following quote partly illustrates this view:

> *The rate equation is written in terms of reactants. This is* $Rate= k. [NO]^2$. *The coefficient of the substance is written as an exponent in the equation. Since the coefficient is two, this is a second order equation.....Here the rate of the reaction will decrease* [as the reaction progresses]. $Rate=k. [NO]^2$. *Catalyst, temperature, volume, pressure and concentration affect the rate of a reaction. Since temperature does not change, our k value will not change. However, as the concentration of NO decreases, our rate will decrease.* [A student's response to Questions 4a and 4b].

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. The student was not aware that the order of a reaction must be determined experimentally. Some of the students did not take into account the experimental data, and some others, as observed by McDermott *et al*. (1987) in other areas of science, had conceptual difficulties in interpreting empirical data, and had difficulties in making

Table 7 The pattern of students' responses to the questions testing the same basic ideas (Post-test)

Questions / Class	Post-test: Control Group (n=36)	Post-test: Experimental Group (n=47)
Q1-Q3	52.8	63.8
Q6-Q8	13.9	70.2
Q2-Q4b	11.1	68.1
Q2-Q9	22.2	68.1
Q4b-Q9	8.3	55.3
Q2-Q4b-Q9	5.5	53.2
Average	19.0	63.1

Notes: Data show correct answers, as %.

connections between a graphical representation (*i.e.* concentration vs. time graph) to the subject matter it presents (*i.e.* the rate concept). For example, in response to question 4b, around 81% of the students in the control group incorrectly related one type of graph (concentration vs. time graph) to another (reaction rate vs. time graph) (see Table 6). As quoted below, students incorrectly interpreted a given graph based on directly observable features of the graph:

> *The rate of a reaction is directly proportional to the concentrations of reactants. Since the concentration of NO decreases, the reaction rate will also decrease.* [A student's response to Question 4b].

The student was apparently focusing on the concentration of the reactant versus time rather than on the slope of the graph. However, unlike students in the control group, students in the experimental group were more likely to correctly attribute the empirical data to the subject matter (*e.g.* see Table 6, Questions 2, 4b and 9). For instance, as quoted below, they consider the reaction rate as the slope of the concentration of reactants vs. time graph; since the slope of the graph is constant at any point, they assume that the reaction rate is constant during the reaction:

The rate equation is $r_{NO} = k$ *and this is constant. Because another representation of the rate equation is*

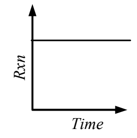
$$r = \frac{Change.in.Concentration}{Time} = \frac{\Delta[NO]}{\Delta t} \rightarrow$$

the slope of the graph [the concentration of reactants vs. time graph] gives us the rate expression and while this is constant, we obtain a zero order equation….Therefore; the rate of this reaction is constant during the reaction. [A student's response to Questions 4a and 4b].

Consistency of answers to questions testing the same ideas

Understanding cannot be observed directly. Students' reasoning may significantly depend on the social and cultural contexts of questions and methods used (Schoultz *et al.*, 2001). Therefore, one way to explore understanding is to look at the consistency of individual students' responses to several questions probing understanding of the same idea (*i.e.* the underlying chemistry is identical in those cases). In order to explore how well students apply their knowledge to a range of contexts, individual students' responses to the questions testing the same ideas were cross-tabulated. If students' reasoning is based on underlying reasoning patterns, consistent responses might be expected to questions testing the same ideas. Table 7 presents the pattern of individual students' responses to these questions. The results showed that after teaching, students in the experimental group were more likely to use their ideas consistently across identical questions than students in the control group (see Table 7). Here are illustrative quotations from a student who appropriately applied his knowledge to two closely related questions:

A student's response to Question 4b:

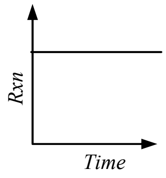


The reaction rate is constant

When we look at the slope of this graph [concentration of NO vs. time graph]:

$$-\frac{\Delta[NO]}{\Delta t} = (constant) = -\ tangent\ \alpha;$$ *therefore the reaction rate is constant.*

The same student's response to Question 9:



The reaction rate is constant

$$V(rate) = \frac{\Delta[G]}{\Delta t}\ ;\ for\ (0\text{-}3)\ seconds$$

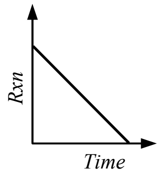
$$V_{0\text{-}3} = \frac{\Delta[0.02-0]}{[3-0]} = \frac{0.02}{3}$$

For (3-6) seconds $V_{3\text{-}6} = \frac{[0.04-0.02]}{[6-3]} = \frac{0.02}{3}$;

$V_1 = V_2 = V_3 = V_4 =$ *Constant. Therefore, the reaction rate is constant*

Nonetheless, as shown below, although some students gave a correct answer to one question, many of these students gave the wrong answers to other questions dealing with the same chemical concepts.

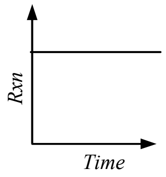
A student's response to Question 4b



The reaction rate decreases

As can be understood from the graph [concentration of NO vs. time graph], since the slope is constant, we can say that the reaction rate is directly proportional to [NO] *(concentration of NO)…. As V(rate)= k. [NO], the rate of reaction is directly proportional to [NO]. Thus, the reaction rate vs. time graph will be the same as the concentration vs. time graph.*

The same student's response to Question 9



The reaction rate is constant

Time intervals are equal in the table. Each interval is 3 minutes. However, the concentration of G increased equally in each time interval. It increased 0.02 M in each interval. Since time intervals and the production of G in these time intervals are the same, the rate [of this reaction] is constant. I can confidently say that the rate of this reaction is constant.

It seems that when attempting to answer closely related questions on reaction rates (*i.e.* the underlying chemistry is identical in those cases); the student did not use their scientific knowledge in a coherent way over these questions. Average percentage of the consistency of students' application of knowledge to a range of identical questions was 19% for the control group and 63.1% for the experimental group (see Table 7). This finding appears to be in line with the findings reported by other researchers that the settings of a question may affect students' reasoning (Clough and Driver, 1986; Watson *et al.*, 1997), and that advanced science learners are more likely to use their ideas consistently across different contexts than novice learners (Palmer, 1997).

Discussion and educational implications

The evidence-informed instruction enhanced students' understanding of chemical kinetics

In this paper, we have discussed the effects of a teaching intervention, the design of which was informed by evidence from educational theories and research data, on students' ideas in chemical kinetics. This study was based on the notion of evidence-informed practice that, besides other issues, closely links analytical and empirical educational research with the development of teaching interventions (Duit *et al.*, 1997; Leach and Scott, 2002; Millar *et al.*, 2006). The findings of this study suggest that students who have followed the EiI on chemical kinetics show significantly better conceptual understanding in kinetics than that achieved with the traditional instruction. Several reasons may account for this difference. On the one hand, in the EiI, the subject matter to be taught was clarified; students' alternative conceptions were taken into account, teaching goals of chemical kinetics were identified and appropriate teaching tools in order to achieve these goals were developed and implemented. The EiI was also planned to encourage a number of different dialogs between the teacher and students and among students (Mortimer and Scott, 2003). Such structured activities aimed to provide students with opportunities to *explore*, *be aware*, *consolidate and reflect on* their ideas about chemical kinetics, and to be an active and self-reflective learner. On the other hand, the traditional instruction was mainly based on the transmission of knowledge from the teacher to students, without considering students' alternative conceptions and the content structure of the domain. In the traditional instruction, students were passive listeners and the dialog between the teacher and students was rather limited. As a result, students in the CG possessed generally low-level of conceptual understanding of chemical kinetics, and many students hold alternative conceptions about kinetics concepts even after teaching. The results of this study support previous research regarding Turkish students' ideas about chemical kinetics (Cakmakci *et al.*, 2006; Cakmakci, 2010a).

Contextual features of a task may affect students' responses (Watson *et al.*, 1997; Cakmakci *et al.*, 2006); however, our findings suggest that students who have followed the EiI are less affected by contextual features of the task than students who have followed the traditional instruction. Students in the experimental group were as a group showed a fairly high degree of coherence and consistency in their scientifically acceptable knowledge. In contrast, students in the control group showed fairly dramatic inconsistency in their scientifically acceptable knowledge in response to the identical questions (see Table 7). This finding suggests that in order to assess students' understanding of a specific content area, it is necessary to investigate their ideas in a range of contexts.

Towards research evidence based practice

This study articulated ways in which an evidence-informed teaching approach (Davies 1999; Millar *et al.* 2006; Bridges *et al.*, 2009) can be built into the design of a course. The significance of this study is that it provided evidence about the outcomes of the EiI on chemical kinetics, and hence provided a warranted situation for teaching chemical kinetics based on the notion of evidence-informed instruction rather than on those of the traditional instruction. It was discussed how research evidence and scholarly perspective on learning were used to inform the design of the EiI. As discussed earlier, many researchers share the view that educational practice should be more research informed by considering the relationship between research and application of research in classroom practice (Thomas and Pring, 2004; Millar *et al.*, 2006). In this respect, the results of the present study support the view that the notion of evidence-informed practice seems to be a promising avenue to improve students' learning in science (Leach and Scott, 2002; Millar *et al.*, 2006). This approach can be used by other researchers to develop teaching interventions in other areas of science in order to improve students' learning. For instance, the results of this study revealed that students' lack of understanding in thermodynamics and chemical equilibrium significantly influences their ideas about chemical kinetics. Considering interrelationships between these domains and designing, implementing and evaluating these combined teaching units would be considered for future research. In other areas of science, there are some research studies on teaching and learning interventions; however, there are a limited number of research papers that focus on designing and evaluating teaching interventions for several closely related topics.

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