Comparison Of Students' Readily Accessible Knowledge Of Reaction Kinetics In Lecture- And Context-Based Courses

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Abstract

This study examines differences in the ability of undergraduate students, taught in lecture-based or context-based general chemistry courses, to describe reaction kinetics. The subjects included 210 students from a residential science college at a large research university. Two open-ended questions were used to engage students' surface knowledge of reaction kinetics in three classes (two lecture-based chemistry, one context-based chemistry). The constant comparison method was used to generate common themes mentioned by students for a quantitative assessment. The results showed that students in the context-based course accurately discussed mathematics (59% v. 31%), energy (44% v. 7.8%), rate-changing factors (46% v. 22%), and the particulate level (27% v. 14%) significantly more than those in the lecture-based course. Despite a much lower emphasis on quantitative problems, the context-based students were more likely to include accurate equations than their lecture counterparts (51% v. 11%). Through a separate qualitative analysis, half of the context-based and one quarter of the lecture-based responses were judged as good or excellent. These findings provide evidence of the success of context-based learning in providing students with accurate and easily accessible knowledge of reaction kinetics.

Keywords: reaction kinetics, chemical kinetics, general chemistry, undergraduate education, context-based learning

Introduction

Understanding reaction rates, the factors that affect them, and kinetics theories (e.g. collision theory) are necessary for understanding and manipulating chemical reactions (Cachapuz & Maskill, 1987; Cakmakci & Aydogdu, 2011; Justi, 2002; Talanquer, 2016). Reaction kinetics is therefore an important introductory chemistry concept, but numerous research studies have shown that it is one that is challenging for students (Cachapuz & Maskill, 1987; Cakmakci, 2010; de Vos & Verdonk, 1986; Justi, 2002; van Driel, 2002). In their recent review, Bain and Towns (2016), conclude that most of the common alternative conceptions surrounding the learning of kinetics have been identified, including those that conflate kinetics with either thermodynamics or equilibrium (Cakmakci & Aydogdu, 2011; Sozbilir & Bennett, 2006; Turányi & Tóth, 2013). Since Turkey has been a hotbed of kinetics learning research, Bain and Towns suggest that that the most productive research studies will help to confirm the ubiquity of previous conclusions in student populations outside Turkey or, better yet, will identify teaching approaches that effectively address the conflation of kinetics with thermodynamics or equilibrium (2016).

Situated cognition posits that all knowledge is situated in activity within sociocultural and physical contexts, meaning that individuals learn by engaging with meaningful, real-world problems (Brown, Collins, & Duguid, 1989). Although context alone does not ensure that students learn, it provides a framework through which students can become part of a community of practice as they engage with their peers and instructor(s) to gain not only meaningful content knowledge, but also an understanding of the activities and tools experts use when solving problems (Lave, Wenger, & Wenger, 1991). An alternative to traditional lecture, context-based learning has gained popularity (Bennett, Lubben, & Hogarth, 2007; Gilbert, Bulte, & Pilot, 2011) because it requires students to focus on problem analysis, knowledge application, and cooperative work around relevant issues (Dahlgren, 2003; Duch, Groh, & Allen, 2001; Prince & Felder, 2006; Schmidt, 1995). This allows students to encounter scientific concepts when they arise within data or real-world situations, often learning concepts in part and revisiting them in other contexts to gain a deeper understanding (Ramsden, 1997). Multiple studies have found that context-based learning increased students' conceptual understanding, retention and synthesis of knowledge, inquiry-related skills, and/or interest in the subject across a variety of STEM fields (Allen, Duch, & Groh, 1996; Allen & Tanner, 2003; Hmelo-Silver, 2004).

Since context-based learning encourages students to build their understanding around real-world situations, it is reasonable to expect that students' understanding of core concepts and their relationships may be different than those taught in a more traditional course. The ChemConnections modules ("W. W. Norton & Company," n.d.), employed as the context-based approach in this study, were developed by the NSF in an effort to re-envision the first two years of university chemistry. These learner-centered modules use question-driven, real-world problems as the context through which students explore, apply, and understand core chemical principles like scientists (Anthony et al., 1998; Russell et al., 1997). Ideally, the modules address five major problem areas in science education: curriculum overload, isolated facts, lack of transfer, lack of relevance, and inadequate emphasis (Gilbert, 2006; Gilbert et al., 2011). The modules place greater emphasis on conceptual understanding and contextual implications than computational skills (for a more complete description see (Anthony et al., 1998)). Additionally, they do not isolate topics by chapter, thus students are more likely to have to negotiate the similarities and differences between kinetics and other topics, such as thermodynamics and equilibrium.

Research aims, study significance, and reasoning behind topic choice

There is a greater need to understand the impact of different teaching approaches than catalogue student misunderstandings of reaction kinetics (Bain & Towns, 2016). Unlike more in-depth assessments of student understanding (Cakmakci & Aydogdu, 2011; Sozbilir & Bennett, 2006; Turányi & Tóth, 2013), this study compares the effects of a context-based approach to a lecture-based approach on the knowledge that undergraduates readily access about reaction kinetics given minimal prompting. While traditional lecture-based approaches typically isolate concepts into distinct units or chapters, context-based approaches allow students to encounter chemistry concepts multiple times through the use of multiple modules during a course. Through these encounters, students gain multiple perspectives on a concept which may result in differences in knowledge structures. Our research question thus asks, "Is there a difference between the readily accessible knowledge of a student who participated in a context-based versus an active-lecture approach?" We define 'readily accessible knowledge' as the network of ideas and relations, that an individual immediately remembers and employs when prompted by the name of a concept; similar to what a student faces when previously-learned concepts are mentioned in a subsequent course.

	Lecture Based Chemistry (LBC)	Context Based Chemistry (CBC)
Format	Active lecture involving discussion and clicker questions	Student-focused group work with instructor-led discussions
Class time/week	Three 50 minute lectures One 50 minute recitation One 3 hour lab	Three 50 minute lectures One 50 minute recitation One 3 hour lab
Year of study (sections)	2 (2 sections)	1
Number of students	151	59
Major assessments	4 exams (3 mid-term + final)	One paper, one poster, one presentation, oral final exam
Recitation format	Worksheet of quantitative exam questions guided by learning assistant	Continuation of module activities led by learning assistant
Laboratories	13 lab periods with mostly one-week experiments aligning with lecture content	11 lab periods of multi-week experiments linked to module content
Homework	Weekly online electronically graded assignments	Approximately weekly written reflection assignments

Table 1. Comparison of the Lecture-based and Context-based Chemistry Courses

Classroom context & participants

This study examined two teaching approaches to the second semester of an introductory general chemistry course at a residential undergraduate college dedicated to studying the natural sciences in their historical, philosophical, and social contexts (Sweeder, Jeffery, & McCright, 2012). Students enrolled in either course took a lecture-based first semester of general chemistry with one of three instructors. During the second semester, two sections were taught as a lecture-based course with active learning (LBC), and a third section as a context-based modular course (CBC). The two lecture sections took place one year after the other course (see Table 1) with the instructor that taught the CBC course. Reaction kinetics was introduced during the second semester of general chemistry.

A comparison of the LBC and CBC courses is shown in Table 1. The LBC lecture was primarily dominated by the instructor, but included some significant student collaboration on problems and collection of responses using a clicker system. On the three unit and final exams, students were required to provide written descriptions of chemical concepts and complete quantitative problem solving in roughly equal amounts. Each of the three 3- to 4-week modules for the CBC were selected to align with the topics covered in the LBC. The students in this course had the same in-class time commitment as the LBC students, but two fewer lab periods. Furthermore, their recitation session was typically an extension of the lecture where students would continue module work with an undergraduate learning assistant. The modules' laboratory experiments were aligned with the classroom activities. Students completed approximately weekly homework assignments with mostly qualitative problems (see Table S1). The students were assessed at the end of each module through papers and/or presentations. For the last three weeks of the course, the students investigated a topic of their choosing (e.g. fireworks, food science) in small groups and completed a final project. In place of the final two labs, students had the opportunity to practice with their laboratory learning assistant for their final assessment: an up to 45-minute oral final with the course instructor during the last two weeks of the course (Sweeder & Jeffery, 2012).

The research was approved with the MSU IRB (#x05-673). The study population included mostly first-year undergraduate students enrolled in the LBC (N=151) or CBC (N=59). Students in both classes had equivalent average general chemistry I grades (83.7 and 83.4, respectively) and were drawn from all quartiles based on their general chemistry I performance (Figure 1). 53% v. 55% of the students were female in the LBC and CBC courses, respectively.

The timeline for coverage of kinetics-related topics in each course is shown in Figure 2. In both approaches, the basics of reaction kinetics are discussed early in the semester and subsequently revisited through the topic of nuclear decay (see yellow and orange lines on Figure 2). In both approaches, approximately the same time was spent on in-class instruction of kinetics, though its distribution differed. Each course completed two kinetics-related labs: the rate of reaction between bleach and dye (Sweeder & Davis, 2009) and mechanism determination in the blue bottle experiment (Wellman & Noble, 2003) in the LBC; and an iodine clock reaction lab and a three-week hydrolysis of cytosine lab (Dworkin, Jasien, Levy, & Miller, 2004) in the CBC (see Figure 2). The time between instruction of kinetics and completion of the assessment instrument was approximately 33 days for the LBC and 19 days for the CBC. Considering the subsequent radioactive decay lectures, the difference drops to 5 and 14 days for the LBC and CBC, respectively.

Instrument development and data collection

The instrument used to assess students' readily accessible knowledge of reaction kinetics consisted of two open-ended questions. After a pilot test with over 35 fourth-year pre-service science teachers, a concealed hint was added which students were informed they could use with no penalty. The role of the hint was to provide a basic definition for those students who had no initial recollection of the topic. Three instructors of the course confirmed the face validity of the questions and felt that they were appropriate for the course level and content. The instrument read:

1) Explain the scientific concept of reaction kinetics in as much detail as possible.

2) Provide a real world example where reaction kinetics are present and explain their role. Use writing, equations, and a drawing to explain.

Hint: Reaction kinetics, also known as chemical kinetics, is the study of rates of chemical processes.

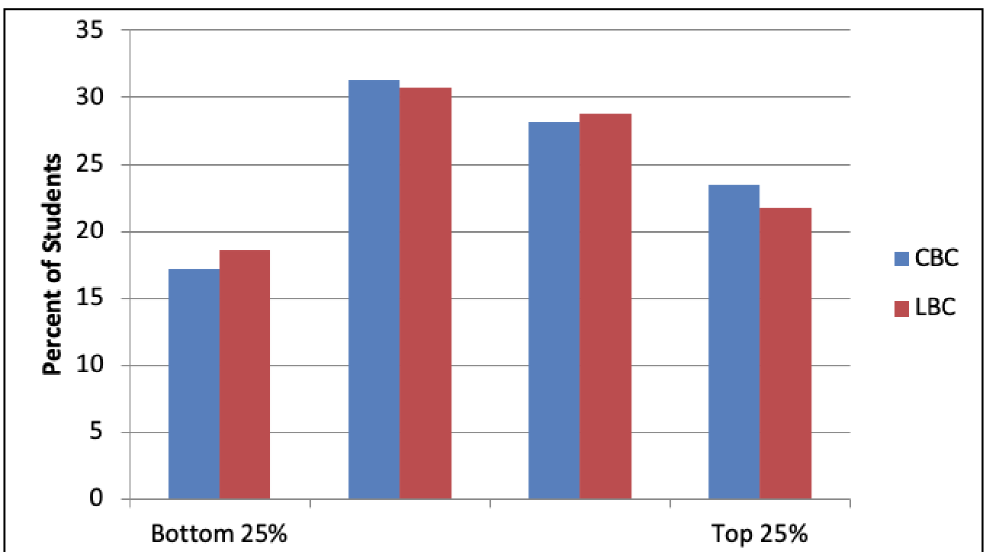

Figure 1. Percent of students from each quartile based on General Chemistry I final grade

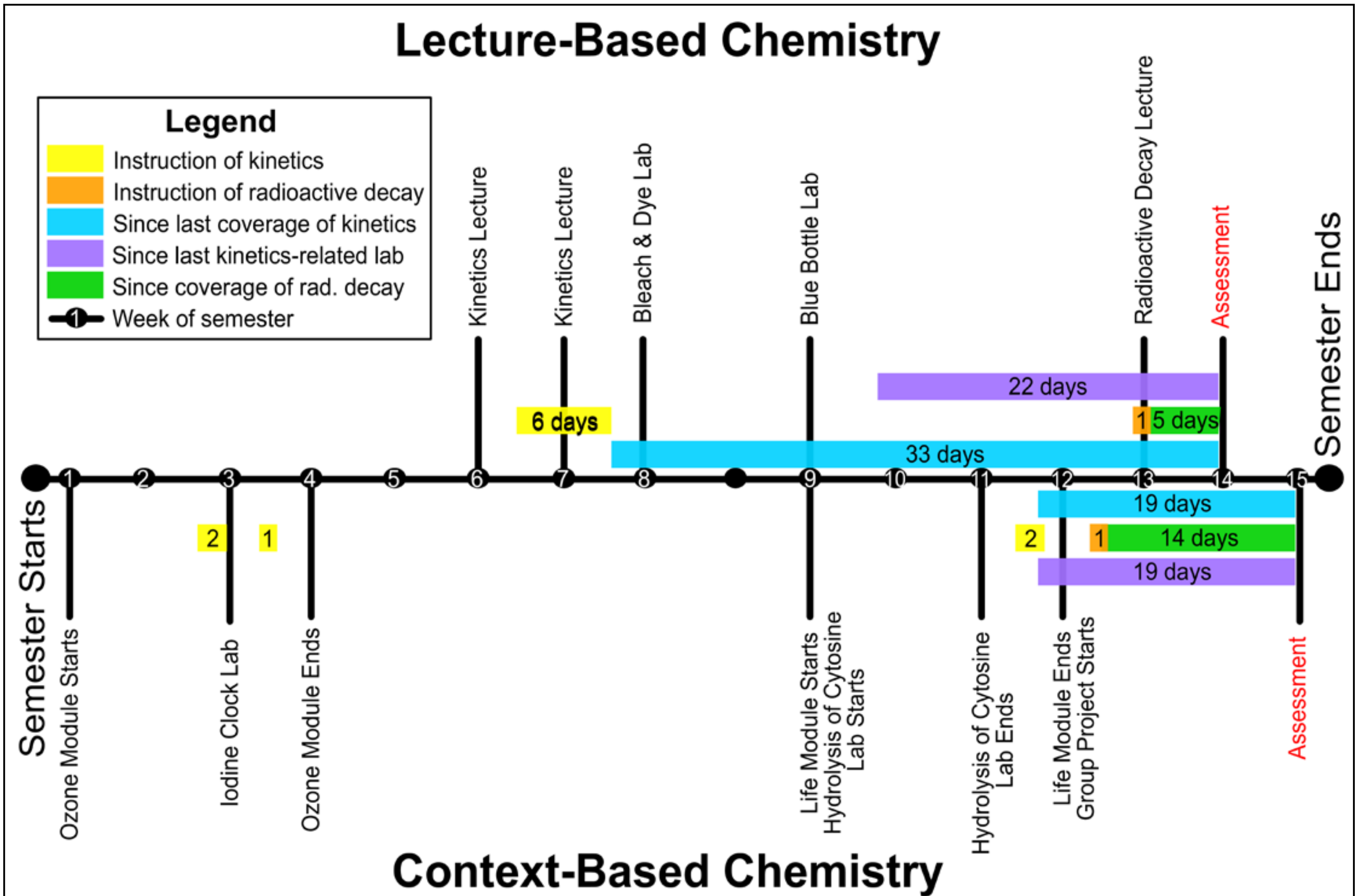

Figure 2. Timeline of topics covered in lecture-based and context-based general chemistry II course. Numbers on the black line represent the week of the semester.

During a normally scheduled lecture, the instructor reminded students in each section that the instructors are constantly tweaking the course and wanted to evaluate a change they had made earlier in the semester by gauging the students' understanding of a previous topic with a short, ungraded, individual assignment. The students were given seven minutes to answer the two questions above. By design, the prompt was low-risk, both in its presentation and open-ended nature. It was kept short to engage students' surface knowledge of reaction kinetics rather than deeply probe their understanding, simulating how they might need to immediately access that knowledge when encountering a concept in a subsequent course.

Data analysis

All responses were analyzed using constant comparison to generate six common themes with descriptors (see Table 2) (Strauss & Corbin, 1990) . Many real-world examples (second instrument question) were extensions of students' responses to the first question, therefore answers to both questions were considered collectively during analysis. Inaccurate responses were afforded their own sub-category if they fell within one of the common themes, but responses unrelated to kinetics or which indicated a lack of even surface knowledge were not counted. To evaluate the reliability of the coding scheme, two raters independently coded all of the student responses. The results were compared and categories slightly re-defined. Both raters then separately re-coded all of the responses and calculated a Cohen's kappa inter-rater reliability value of 0.87 (ranged 0.81-0.90 for individual classes). Disagreements were mutually re-evaluated and assigned a final coding. Cross-tabulation and a z-test of proportions were performed on the final results using SPSS (*IBM SPSS*, 2017) to gauge significant differences between the percentage in each category for the two approaches. Odds ratios were used as a measure of effect size (Wilson, 2018). The students' responses were also assessed qualitatively on a scale which is described with illustrative quotes in Table 5, and the percentages in each category were again compared with a z-test of proportions. For the qualitative analysis, a rater not involved in the quantitative analysis evaluated each response holistically as "excellent", "good", "moderate", or "weak" as they might when grading. The rater also evaluated the quality of the example provided. They were unaware of which course the student responses came from during the rating process.

Results and Discussion

Combining quantitative and qualitative evaluation provided a more comprehensive picture of students' readily accessible knowledge of reaction kinetics. The quantitative analysis indicated that CBC students more frequently discussed mathematics, energy, rate-changing factors, and the particulate level; the LBC students more frequently discussed mechanisms. Significantly, more CBC students discussed three or more themes in their descriptions. Qualitative analysis indicated that significantly more CBC students provided descriptions that were categorized as 'good' or better. Each of these findings is described in more detail below.

Quantitative analysis

Table 3 provides the percent of students that mentioned each common theme in the two approaches. There were significant differences in student ability to describe all themes except 'definition' and a higher percentage of CBC students discussed all themes excluding 'mechanisms'. The most notable differences were the presence of accurate equations and discussions of energy (Table 3). Additionally, a higher percentage of CBC students used three or more

Theme	Description	Illustrative Quotes
Definition	Without opening the hint, refer to rate or speed of the reaction. May simply refer to a reaction as being 'slow' or 'fast'.	"Reaction kinetics is the speed at which a reaction takes place." (LBC)
Mathematics	Refer to rate laws/equations, rate constants (k), or the orders of reactants/reactions. May provide a basic rate law, an integrated rate law, or a half-life equation as examples.	"Reaction kinetics relate to rate laws and the speed of the reactions. $Rate=k[A]^a[B]^b$ is the rate for equations such as $aA + bB \rightleftharpoons cC + dD$. k is the rate constant that is specific to the reactants in a equation. The rate above is correct assuming the reaction is an elementary step." (CBC)
Rate-Changing Factors	Refer generally or specifically to factors that affect the rate of a reaction. Commonly mentioned factors include concentration, temperature (heat), pH, catalysts, and pressure.	"There are a number of things that can increase reaction kinetics including pH change and an increase in temperature."(CBC)
Energy	Refer to energy changes during a chemical reaction. May mention activation energy or provide a suitable reaction coordinate diagram.	"Upon heating some substances the molecules will have more energy and will be moving more quickly. This makes the molecules more likely to collide and interact with each other." (CBC)
Mechanisms	Refer to steps or mechanisms of a reaction. May mention relative speed (fast/slow) of steps or the rate-determining nature of slow steps.	"...a more in-depth look into the 'arrow'. This takes into account various chemical mechanisms. The slowest step of the reaction is said to be the rate determining step and then a rate expression is made from that step..." (LBC)
Microscopic Level	Refer to interactions between particles involving collisions or orientation, or relative movement of particles.	"Collision theory states that atoms and molecules have to collide in the correct orientation in order to form a bond. Kinetics is a way to talk about how often these collisions occur." (CBC)

Table 2 Common themes and descriptors generated from student responses for quantitative analysis.

Theme	Lecture-based Chemistry (N=151)	Context-based Chemistry (N=59)	Odds Ratio
Definition†	52	46	
Mathematics (fully accurate)*	23	59	4.8
Including partly inaccurate*	26	63	4.8
Fully accurate equations only*	11	51	8.4
Rate-Changing Factors*	26	46	2.4
Energy*	16	36	3.0
Inaccurate	23	10	
Mechanisms*	31	12	0.30
Particulate Level	17	27	
Three or more accurate themes*	22	36	1.97

*Denote categories that differed significantly from each other at the 0.05 level via a z-test of proportions with Bonferroni correction.
†Value does not include students who opened the hint.

Table 3. Percentage of students that mentioned common themes.

Conflated Concept	LBC (N=151)	CBC (N=59)
Equilibrium*	7.9	0.0
Equilibrium expression	2.6	6.8
Thermodynamics	7.3	5.1

*Denote categories that differed significantly from each other at the p<0.05 level using z-test of proportions with Bonferroni correction.

Table 4. Percent of students that conflated reaction kinetics with another concept.

themes in their descriptions (37% v. 17%, Odds Ratio (OR) = 2.9, 95% CI [1.5, 5.6]). There was also a significant difference between the percentage of students that opened the hint in the CBC versus the LBC (27% v. 11%, OR = 3.3 95% CI [1.5, 7.1]). The data suggests that the CBC students have more readily accessible knowledge when prompted to explain the concept of reaction kinetics.

Mathematics

Reaction kinetics can be explained qualitatively through particulate models or quantitatively via mathematical models, though the emphasis of university-level courses rests primarily on the latter (Cakmakci et al., 2006). Interestingly, a higher percentage of CBC students provided symbolic (equations) or written explanations of mathematical relationships in their responses. This is noteworthy as the CBC approach places far less emphasis on mathematical calculations than the LBC instruction. Furthermore, on mid-semester and end-of-semester course evaluations, CBC students expressed worry about falling behind their LBC counterparts due to less emphasis on and experience with quantitative problem solving; yet this evidence suggests they more readily access mathematical knowledge about reaction kinetics. Several end-of-semester comments like the following suggest that some students sense this difference:

> I feel that I learned more from this semester. I have already forgot how to do much of the math problems from last semester but the things I learned this semester I can actually explain why so the concepts stick better.

Approximately the same percent of students in each course provided inaccurate equations by combining rate and equilibrium expressions (Table 4). Previous studies have found that students conflate reaction rate with LeChâtelier's principle (Cakmakci, 2010; Garnett, Garnett, & Hackling, 1995; Johnstone, MacDonald, & Webb, 1977) and extent of reaction (Wheeler & Kass, 1978), independently changing rates of forward and reverse reactions at equilibrium when conditions are changed (Hackling & Garnett, 1985). While 7.2% of LBC students also conflated these concepts in their qualitative descriptions, none of the CBC students appeared to do so (p=0.035, Table 4). This suggests that the CBC approach may have supported students' negotiation of distinctions between reaction kinetics and equilibrium. However, multiple students discussed "controlling" a reaction by changing conditions. It was not clear if these students were confusing the concept of manipulating a reaction *rate* with manipulating an *equilibrium*, indicating that care needs to be taken towards making this distinction.

Rate-changing factors

A significantly higher percentage of CBC students mentioned general or specific factors (e.g. pH, temperature, etc.) that could influence reaction rate (46% v. 22%, p=0.00012). This count includes those students that mentioned the influence of "environment" or "conditions" on reaction rate in their response. LBC students were introduced to rate-changing factors via examples in lecture and two kinetics-related labs, including one specifically focused on the impact of changing concentration on reaction rate. Despite this, of the 39 LBC students who indicated that conditions could change rate, 18 specifically cited catalysts as a rate-changing factor. In contrast, CBC students generally focused on the ability to change conditions (18%) or mentioned specific conditions such as temperature or reactant concentration (13%). Surprisingly, no CBC students specifically mentioned catalysts. The CBC modules supported students' ability to describe the effect of these factors on reaction rate: in class, students explored how the rate of ozone destruction/synthesis changes as altitude (and thus temperature and concentration) varies, as well as how the rate of hydrolysis of cytosine to uracil is affected by temperature, pH, and concentration, in lab. Even though the LBC students explored the same concepts, the CBC students more readily mentioned how to manipulate rate-changing factors, and the results of doing so for a particular system.

Energy

A much higher percentage of CBC students (44% vs. 7.8%, OR 9.1, 95% CI [3.2, 20.0]) accurately discussed energy in their responses. Not surprisingly, students in both courses equivalently showed commonly reported alternative conceptions: 10% of the CBC and 13% of the LBC responses discussed energy inaccurately, with 5.1% of the CBC and 5.6% of the LBC conflating kinetics with thermodynamics, which had been discussed at the end of the previous semester. It seems that neither approach was better at avoiding the conflation of kinetics that arises, likely because most students have a superficial understanding of thermodynamics (Bain, Moon, Mack, & Towns, 2014; Carson & Watson, 1999; Sozbilir, 2002; Sozbilir & Bennett, 2006; Sözbilir, Pınarbaşı, & Canpolat, 2010). Cakmakci (2010) suggests that this conflation may come from the tendency of many curricula to teach these concepts separately. The CBC attempted to highlight the differences between thermodynamics and kinetics with a session discussing what is meant by a 'stable' molecule. This may explain responses like the following:

> Reaction kinetics is the idea of whether or not a rxn actually occurs. Some rxns are thermodynamically favorable but won't occur/will occur extremely slow because the Ea is too high. Combustion is a good example. Thermodynamically favorable but won't occur without input of outside E.

Three (2.0%) LBC students compared to 22% of CBC students discussed how the *addition* or *availability* of energy affected a reaction's ability to proceed. It appears that requiring the students to explicitly grapple with kinetic and thermodynamic stability (versus examples given by the instructor in the LBC) had an impact on students' ability to directly recall this differentiation.

Particulate level

There were two different ways the students talked about the particulate level: in terms of particle motion or reaction mechanisms. A statistically higher percentage of CBC responses discussed movement or interaction of particles than the LBC responses (27% v. 14%; Table 3). Discussions of kinetics at the particulate level were infrequent across both courses which is consistent with previous work indicating that students tend to use macroscopic explanations of reaction kinetics over particulate and mathematical explanations (Cakmakci, Leach, & Donnelly, 2006). The LBC had a higher percentage of students that discussed mechanisms (31% vs. 12%) which may reflect the emphasis the instructor placed on mechanistic explanations, causing it to become a key concept for students. Although mechanisms were also discussed in the CBC, the

Description Scale	Illustrative Quotes	Percent	
		LBC (N=151)	CBC (N=59)
Excellent: definition, discussion of multiple concepts and no inaccuracies	"Reaction kinetics are determined by a variety of factors. The rate of reaction can change depending on the pH of a solution, the temperature of the solution, or the concentration of reactants. Temperature can increase the speed of a reaction because it increases the speed of a reaction because it increases the amount of collisions that occur..." (CBC)	11	20
Good: definition, discussion of one concept or multiple with inaccuracies *	"Rxn kinetics is the series of steps a reaction undergoes to reach the desired products it contains a slow step which determines the rate of the rxn." (LBC)	13	31
Moderate: definition, discussion with minor inaccuracies*	"...studies the rate law of reaction to see how long (or even if) the reaction will take. k is the rate constant that is determined by [products]/[reactants]. Then to find the rate law is k* [products]/[reactants]. k can be found experimentally. It is affected by both pH & temp..." (CBC)	39	20
Weak: definition, but no evidence of understanding; inaccurate or possessing major fallacies	"Has to do with how fast a reaction takes place. Rate of reaction." (LBC) "Reaction kinetics is the transfer of energy within a reaction process. With reaction kinetics we can look inside a process and see what is happening." (LBC)	37	29
Example Scale	**Illustrative Quotes**		
Example with explanation	"...how quickly medicine works in the body and how long it will last. If you are a doctor doing surgery you don't want to give your patient so little anesthetic that they wake up..." (LBC)	21	20
Potential good example with some inaccuracy	"...lighting a match and the combustion reaction. This reaction occurs b/c the match provides friction which is also the activation energy and provides enough; $C_xH_{2x} + O_2 \rightarrow CO_2 + H_2O$; rate=k[$CO_2$][$H_2O$]" (CBC)	9.3	3.4
Potential good example, but no evidence of understanding	"A real world example is studying the reaction kinetics of hazardous materials mixing. Knowing the rate of reaction will help you to solve the issue before it is too late." (CBC)	30	42
Poor/unrelated example or major fallacy*	"Mixing chemicals together." (LBC)	26	12
Blank or invalid example	"Macaroni + $H_2O \rightarrow$ Macaroni H_2O; add heat increase speed of absorbance." (LBC)	13	22
Provided kinetics-related drawing		13	20

*Denote categories that differed significantly from each other at the 0.05 level.

Table 5. Qualitative scale for student descriptions and real-world examples, and percent of student responses in each category.

instructor's personal focus may have been hidden in the student-driven style of the CBC course.

Interestingly, the sum of these two particulate-level groups are quite similar between the two courses. However, the data indicate that when the students were prompted with the idea of reaction kinetics, the CBC students were much more likely to respond with descriptions of molecular motion and interaction of particles, whereas the LBC students responded with reaction mechanisms. This suggests the importance of context in influencing students' readily accessible knowledge.

Qualitative analysis

The student responses were also analyzed by a rater not involved in the quantitative analysis in order to get a general impression of the quality of student responses. This led to two notable observations: a greater number of higher quality responses came from the CBC students, yet neither group of students was better at providing real-world examples. A higher percentage of CBC responses were categorized as 'good' or better (51% v. 24%; qualitative scale in Table 5). It should be noted that some students interpreted the question differently (1 LBC, 13 CBC), focusing either exclusively or in part on kinetic versus thermodynamic stability, however such responses were still evaluated on a similar scale for quality. Differences in response quality may arise from a combination of several factors, including the CBC students' seemingly better synthesis of reaction kinetics which is in line with previous research (Dolmans & Schmidt, 1996; Gutwill-Wise, 2001; Ramsden, 1997), or greater experience with writing about chemical concepts. CBC students seemed to recognize a difference in their comprehension as expressed in end-of-semester survey comments like the following:

> I feel that I was presented with the same amount of information as in [Chem I] but I retained the information differently. From [Chem I] I retained information needed to solve specific problems effectively. [Chem II] gave me a better idea of how to break down and solve more general problems from the world. I also feel like the format of learning in the class offered a better platform for entering into several other science classes beyond chemistry.
>
> I learned a lot more this semester. The difference was huge. I didn't just memorize information and then forget it after the exam; I actually recall and comprehend the concepts that we went over in class.

Despite learning about kinetics in the context of real-world problems, it was surprising that students in the CBC were no better at providing good real-world examples (Table 5). More CBC examples were actually categorized as blank or invalid (22% v. 13%), though this was not statistically significant. This percentage is slightly misleading because it includes students that indicated they ran out of time. Most students stopped writing before seven minutes passed in all classes, but 6.6% of LBC students and 19% of CBC students indicated that they ran out of time. However, the majority of these responses received at least a moderate rating.

A greater number of CBC students also provided kinetics-related drawings such as reaction coordinate diagrams or graphs (20% v. 13%). Other drawings were provided (e.g. generic glassware, Bunsen burners, smiley faces, etc.), but did not advance students' explanations. This is a surprisingly small number of useful drawings from the entire population given the prompt to use drawings and raises interesting questions about the tendency and/or ability of students to provide meaningful visual representations of chemical concepts.

Study limitations

For practical reasons, this study compares courses taught in two different years. However, the student populations are comparable given similar performance in their general chemistry I courses and similar composition across the quartiles, as indicated by Figure 1. Students may also have self-selected into the CBC course because of the alternate approach. This could bias the differences; however, Figure 1 again suggests a similar composition of student ability.

Although the instrument used in this study could be perceived as a limitation, it was not the authors' intention to deeply probe students' understanding of a few specific topics. Rather, the intent was to investigate students' ability to articulate readily accessible surface knowledge of reaction kinetics. The authors believe that the ability to immediately access previously learned concepts from a short cue accurately reflects how students will use their learning in subsequent courses. Additionally, students' descriptions of reaction kinetics were not elicited prior to this study and therefore progression in understanding cannot be evaluated.

Implications

This study has two main implications regarding approaches to teach reaction kinetics. First, the results of this study suggest that the CBC approach had a positive effect on student ability to describe reaction kinetics in comparison to students taught in the LBC. Specifically, half of the students were able to provide qualitatively "good" or "excellent" responses compared to just under one quarter of the LBC students. Quantitatively, this is also reflected in the increased percentage of CBC students (36% vs. 22%) that accurately addressed three or more themes. Interestingly, although the CBC emphasized mathematical problem-solving significantly less, the students were better at describing the quantitative aspects of kinetics, including providing accurate equations. This is striking given that some CBC students' expressed worry that the lack of quantitative problem solving skills would hinder them in future classes. It is possible that CBC students' more integrated answers were a result of extended discussion around specific examples and re-visiting the same concept in different ways. This may have helped students identify and focus on important ideas and relationships. However, given the surface level nature of the assessment, it is not clear if the CBC and LBC students would prove equally knowledgeable given stronger probing questions.

Second, we observed that explicit introduction of the relationship of both thermodynamics and equilibrium with kinetics, though introducing some confusion, appears to have enabled students to negotiate connections between concepts to better understand their distinctions. Thus, in any discipline, it may be useful to teach frequently confused concepts together to allow students the opportunity to negotiate and articulate their relationship.

Future research needs to explore how revisiting similar concepts from different perspectives and negotiating related but distinct concepts affects students' knowledge and ability to navigate problems. In the context of reaction kinetics specifically, this means future studies should investigate how student understanding changes with the use of activities targeted at relating reaction kinetics, equilibrium, and thermodynamics. More generally, we wonder: What kinds of activities or reasoning tasks support students in distinguishing and negotiating related concepts? In what ways does exploring a concept in a single context support the development of understanding when the same concept is re-visited in different contexts?

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