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Scientific paper

Uncovering Students' Genuine Misconceptions: Evidence to Inform the Teaching of Chemical Kinetics

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Abstract

The aim of this study is to investigate first-year university students' misconceptions in chemical kinetics by analysing data obtained from the four-tier diagnostic instrument of chemical kinetics (FTDICK). 335 first-year chemistry students from two Indonesian and one UK universities participated in this study. The procedure described here is the first of its type to ensure those misconceptions are genuine. Numerous genuine misconceptions within chemical kinetics were revealed among first-year chemistry undergraduates. Although many of the misconceptions found here concur with those results previously published using other instruments, some novel findings were uncovered. These misconceptions can be attributed to a variety of factors including mathematical weakness, carelessness and difficulty in interpreting and extracting information from diagrams, graphs and other non-textual information. On the basis of the results from this study we make some recommendations for improving the effectiveness of chemical kinetics' teaching at this level.

Keywords: Four-Tier Instrument, Teaching Chemistry, Students' Confident Rating, Spurious Misconception

1. Introduction

Chemical kinetics is an essential area of the chemistry curriculum at both secondary and tertiary levels. In some secondary school curricula of some countries, the terminology of reaction rate is preferable. The topic has been of concern to chemical education researchers over the last decade who have long recognised the difficulties students encounter with some concepts. The topic of chemical kinetics has links to many other areas of the chemistry curriculum. It relates to thermodynamics, equilibria, particle theory and aspects of both inorganic and organic chemistry mechanisms.[1] Its applications in industrial processes including the pharmaceutical, agricultural, food and manufacturing industries, the environment and the atmosphere make it a topic whose understanding is of paramount importance to the majority of graduates of science and life sciences degree programmes. Understanding how to measure and control a reaction rate is fundamental to many of these industries and to academic research in a range of disparate disciplines. This understanding is predicated on an appreciation of the particle nature of matter, kinetic molecular theory, the dynamic aspects of chemical reactions including collision theory and transition-state theory,[1–3] all of which are required for success in mastering chemical kinetics. For these reasons a thorough understanding of the concepts is imperative for a whole range of students and educators.

1. 1. A Review of the Literature on Educational Studies in Chemical Kinetics

One recent publication contains an excellent review of research on the teaching and learning of chemical kinetics [4] and provides a useful summary of student and teacher approaches to the subject. Bain and Towns reviewed a total of 34 publications in English focussing on both secondary and tertiary education. It was a requirement of the studies reviewed that they used instruments such as diagnostic tests and presented data and analyses to answer a proposed research question.

The majority of publications in the chemistry education literature focus on the ideas and concepts students of chemical kinetics develop that do not align with those of the scientific community.[2] Understanding of the meaning of reaction rate is key to progression in the subject. Confusion over reaction rate and reaction time has been observed.[5–7] Several studies report the misconception that reaction rate depends upon the stoichiometry of the reaction.[5,8] Elementary studies in the subject may result in the assumption that reaction rate is always dependent upon reactant concentration.[9] A widely held misconception revealed in several studies is that an increase in reactant concentration always results in an increase in reaction rate [5,10–12] including in zero-order reactions.[3] Students have been shown to have varying ideas of how rate changes during a chemical reaction. Some report that rate increases to a maximum and then remains constant for a time before decreasing to zero.[5,6] Others report that rate decreases to a minimum value then remains constant [9] or that it increases or decreases as reaction proceeds.[3,5,8,13] Another misconception is that rate is a constant for any order of reaction.[5,8,9]

The concept of reaction order is one that provokes the most misconceptions. Probably one of the most common misconceptions is that the rate law can be derived from the stoichiometric equation for the chemical reaction.[5,11,14,15] Other common misconceptions include the belief that increasing the concentration of a reactant always increases the rate [10,12,15] with a linear relationship between concentration and reaction rate,[5] and that a change in concentration of a reactant that is zero-order affects the reaction rate.[3]

Bain & Towns[4] concluded that more research is needed into the area of teaching and learning in chemical kinetics at the undergraduate level. Although undergraduate students have similar misconceptions to secondary school students in certain concepts,[5] there are far fewer reports in the literature at the tertiary level. Interestingly, Kolomuc & Tekin[9] found that some chemistry teachers hold similar misconceptions to grade 11 school students, for example regarding the effect of a catalyst on reaction rate.

There are a number of reasons as listed below and given in the review of Bain and Towns, that demonstrate that a study of student understanding of chemical kinetics at the tertiary level is timely:[4] the subject is fundamental to many aspects of the chemistry curriculum and has many real-life applications; the subject is perceived as complex and is not well understood and, in some cases, suffers from confused teaching; there are few studies at the undergraduate level that focus solely on the understanding of chemical kinetics; many of the published studies involve pre-degree level students from a single nation (Turkey). Clearly the predominance of findings from a single nation on a subject studied globally could significantly impact upon the overall conclusions.

A variety of tools have been used for exploring student understanding of chemical kinetics and these are categorised in Bain & Town's paper.[4] The format of the tools varies from open-ended and multiple-choice questions through to multi-tier instruments. More recently multiple-tier diagnostic tests have become more widely used in science education research. The first type of such an instrument was developed by Treagust who used a two-tier instrument consisting of an initial tier of multiple-choice questions with one correct answer and a number of distractors followed by a second tier that probes the reason for the selected answer.[16] Although the two-tier instrument is useful in probing student misconceptions and reasoning it is not ideal. If a student is uncertain of the correct answer or how to approach the problem they may select their reason randomly, often selecting the statement of fact with which they are most familiar. This does not mean that they believe their choice of reason is the correct one, just that they believe the reason chosen is a correct scientific statement. A two-tier instrument cannot distinguish between a firmly held reason and a guess or educated guess.[17] To overcome this, three and four-tier instruments have been deployed. Such instruments require respondents to give confidence ratings for their answers and reasons. In a three-tier instrument a mean confidence rating is requested for the answer and reason whereas in a four-tier instrument a separate confidence rating is given for each.

Clearly the four-tier instrument is more useful than the three-tier one. A combined confidence rating leaves uncertainty in the results as to whether the respondent has a certain confidence level in their question, their reason or both. This leads to difficulty in categorising and grading the responses.[18] When a confidence level is attached to both the answer and the reason a greater certainty about understanding and guess work can be achieved.[19] A student with a good understanding of how to solve the problem and why it is correct should display a high confidence level in both tiers. A student with a low confidence in their answer – whether correct or otherwise - and a high confidence in their reason may well have understood and remembered the theory but not how to apply it correctly. The same condition may stand for a student with a low confidence in a correct answer and a low confidence in their incorrect reason. In addition, careful choice of answer and reason distractors on the part of the researcher can provide valuable information on student understanding. The value of a calculated mean confidence rating of both answer and reason should not be understated as it can be useful in providing an overall indication of student understanding of the theory addressed in the question, especially with the additional information relating to confidence in the two tiers.

1. 2. A Comment on the use of Four-Tier Instruments in Classifying Students' Misconceptions

The procedure for assigning students' misconceptions in these previous studies is not fully robust. For example, previous literature reporting the use of four-tier instruments [19–22] applied 6 ratings of confidence, namely: 1 (guess work), 2 (very unconfident), 3 (unconfident), 4 (confident), 5 (very confident) and 6 (absolutely confident). The authors used an average of the confidence rating of the answer tier and the reason tier to determine the overall confidence in the concept investigated with the mid-point value of the scale (3.5) used as the upper limit of a *genuine* misconception. For example, of confidence rating of 6.00 (absolutely confident) in the answer tier and 2.00 (very unconfident) in the reason tier would result in an overall confidence rating of 4.00, suggesting there was no issue in the understanding of this concept despite the fact that responses displayed an element of poor confidence.

In addition, in some studies, students' responses were binary (i.e. sure or unsure) which is also unsatisfactory as it gives students little opportunity to express their degree of confidence in the topic.[23,24] However, the procedure in justifying students' misconception in those studies might produce a misjudgment in terms of attributing a lack of knowledge or other random errors to be a misconception. For example, the previous literature in the area of four-tier instrument [19–22] applied 6 ratings of confidence. Literature using this scale (1-6) consider 3.5, i.e. the mid-point of unconfident and confidence, as the limit of a *genuine* misconception.

Employing a confidence rating average between the confidence of answer tier and reason tier to justify a misconception applied in those previous studies in the area may raise a bias and misjudgement. For example, a confidence index of 4.00 could result from absolutely confident (6.00) for A tier and very unconfident (2.00) for R tier and vice versa. Therefore, this limits sound flaw because the point still contains the unconfident element. For this reason, in our study, we avoided employing a confidence average instead of using the confidence for the two tiers as the genuine parameter. In addition, only responses with confidence ratings for both answer and reason tiers of ≥ 3.00 are incorporated in determining students' misconceptions. In other studies,[23,24] students' confidence ratings are applied in two expressions (sure or not sure). Such this procedure cause inflexibility of students to express the degree of their certainty or confidence rating. The misconceptions identified in this study can be relayed to university authorities, particularly in Indonesia, and deployed in updating the chemistry curriculum for first-year students. Linking information from students' work to curriculum revision is a productive strategy for informing and underpinning science teaching and educational development.[25]

1. 3. Purposes of the Study and Research Questions

In an extensive review of Chemistry Education Research (CER) Cooper & Stowe[26] highlighted three important aspects of educational research: the knowledge students should master in a topic and how they apply the knowledge; ensuring students have hold robust scientific concepts; supporting students in their learning based on the evidence of their knowledge. Although they did not outline a single strategy to ensure students' scientific understanding, employing a proper assessment procedure is a powerful tool for understanding the nature of students' knowledge framework, including their misconceptions and prior knowledge. We believe that the FTDICK instrument is a powerful tool that can be used to uncover the students' actual misconceptions and allows these misconceptions to be used as evidence in developing good teaching practices in chemical kinetics. Therefore, this study aims to investigate first-year university students' misconceptions of chemical kinetics by analysing data obtained from a four-tier diagnostic instrument. The goal is to use the findings of the study to enhance the teaching of chemical kinetics, especially at the university level, and to improve student understanding.

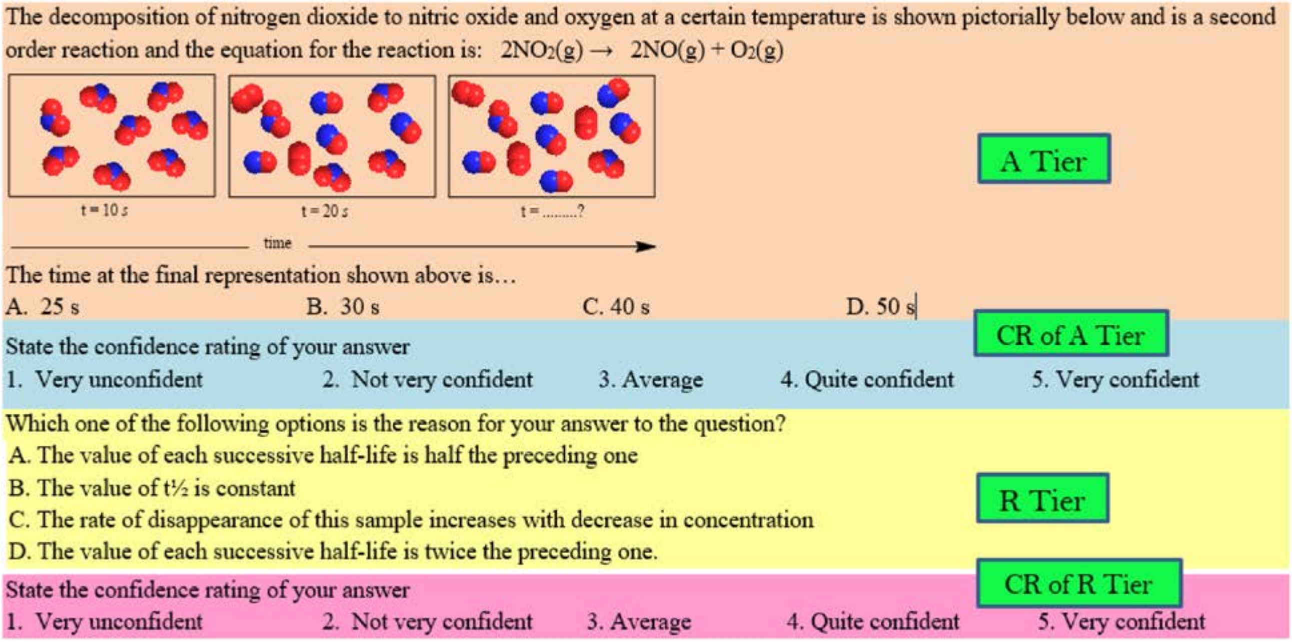
2. Method

2. 1. Participants

This study involved 83 first-year chemistry students at the University of Reading, UK and 252 students at two Indonesian universities. The study was carried out during the second semester of the first year at each institution. As explained in the previous paper,[27] all multiple choice questions were presented and answered in English. The data collection had carried out before students embarked to the chemical kinetics topic in their basic chemistry modules. This is to ensure that all respondents hold an equal prior chemical kinetics class experience.

2. 2. Development of the FTDICK Instrument

The detailed description of the development and validation of the instrument (FTDICK) was described comprehensively in previous paper.[27] The validity and reliability of the instrument has been measured and found to be valid and reliable for data collection. All the questions were valid with a confidence level of 95%. The Cronbach Alpha reliability of the instrument was considered acceptable. The final FTDICK consists of 20 four-tier multiple-choice questions with associated reason choices and was used to investigate first-year students' understanding of chemical kinetics (Appendix 1). As highlighted in the previous paper the FTDICK consists of an answer tier (A tier) and a reason tier (R tier), each with a confidence rating attached. The confidence ratings were scaled from 1 (very unconfident) to 5 (very confident). An example of a four-tier question in the FTDICK instrument is depicted in Figure 1.



The decomposition of nitrogen dioxide to nitric oxide and oxygen at a certain temperature is shown pictorially below and is a second order reaction and the equation for the reaction is: $2NO_2(g) \rightarrow 2NO(g) + O_2(g)$

The time at the final representation shown above is…

A. 25 s B. 30 s C. 40 s D. 50 s

State the confidence rating of your answer

1. Very unconfident 2. Not very confident 3. Average 4. Quite confident 5. Very confident

Which one of the following options is the reason for your answer to the question?

A. The value of each successive half-life is half the preceding one

B. The value of t½ is constant

C. The rate of disappearance of this sample increases with decrease in concentration

D. The value of each successive half-life is twice the preceding one.

State the confidence rating of your answer

1. Very unconfident 2. Not very confident 3. Average 4. Quite confident 5. Very confident

Figure 1. Example of a four-tier question in the FTDICK instrument

Figure 1 displays each tier of the question in a different colour in order to make the tiers more readily identifiable. The first tier consists of a multiple-choice question with one correct answer and three distractors (incorrect answers). The following tier is the confidence rating (CR) for the A tier named CR(TA). The third tier is the R tier and consists of one correct scientific reason and three incorrect and/or unscientific reasons. The fourth tier is the CR for the R tier and is named CR(TR).

2. 3. Research Design and Data Analysis (Grading Schemes)

This descriptive study describes the first-year chemistry students' understanding of chemical kinetics using the FTDICK instrument. The time allocated for students to work on the questions was 120 minutes. Their answers to the FTDICK instrument were the basis for classifying their understanding of the topic. There are four types of combinations of students' answers and reasons, namely: Correct answer and correct reason (CACR) representing good scientific understanding; Correct answer and wrong reason (CAWR) representing a false positive of students' understanding; Wrong answer and correct reason (WACR). This represents a false negative of students' understanding. These categories are not discussed widely in this paper. The wrong answer and wrong reason (WAWR) represents an actual student misconception. We focussed only on WAWR combinations in order to ensure all the misconceptions reported are genuine. The confidence ratings of these schemes are assigned as follows: Option A in Question 1 has a CR(TA) = 4.0 meaning the confidence rating average of all students selecting option A as their answer in the A tier in Question 1 is 4.0. The same procedure is also applied for CR(TR) = 4.0. In this study we avoided using an average confidence rating but focussed on the individual confidence ratings for each tier and only incorporated those that had a rating less greater than 3.00 as indicating a *genuine* misconception.

2. 4. Parameters to Classify Students' Misconceptions

Students' misconceptions were determined based on students' wrong answer – wrong reason (WAWR) combinations. The complete criteria for the classification are given in Table 1 below. As explained in the introduction, although CR(TA) and CR(TR) were obtained from the

Table 1. Criteria used to categorise students' misconceptions based on WAWR incidents

No.	WAWR CR(TA)	 CR(TR)	Category
1.	≥ 4.00	≥ 4.00	*Genuine*: Strong misconception
2.	3.00 ≥ CR(TA) < 4.00	3.00 ≥ CR(TR) < 4.00	*Genuine*: Moderate misconception
3.	2.00 ≥ CR(TA) < 3.00	2.00 ≥ CR(TR) < 3.00	*Spurious*: Weak misconception
4.	<2.00	<2.00	*Spurious*: Lack of knowledge

average of students' confidence ratings in the answer and reason tiers, only those with CR(TA) and CR(TR) of ≥ 3.00 were taken into account to avoid spurious misconceptions, lack of knowledge and possible guesswork.

It has been stated that this paper is derived from the author's PhD thesis. However, the CR values applied to categorise students' misconception is new and more advanced to ensure the genuineness of the uncovered misconceptions.

2. 5. Pre-university Education in Both Countries Regarding Chemical Kinetics

After carefully checking the chemical kinetics content of the A-level chemistry syllabus in the UK and secondary school in Indonesia, we found that the chemical kinetics content for the two countries is equal.[28] Except for Maxwell's distribution, all other concepts in the UK curriculum are accompanied by hands-on experiments. Students in Indonesia are forced to rely on their teachers' explanations and other theoretical exercises to grasp the concepts at hand.

3. Results And Discussion

3. 1. Students' Misconceptions in Chemical Kinetics

The results from our study into students' misconceptions in chemical kinetics have been organised according to the primary concept area in which they lie.

3. 2. Derivation of the Rate Law

Students' misconceptions regarding the rate law were identified using Q4, Q12 and Q17. Several prominent misconceptions were found in this topic.

1. *Concentrations of reactants in the rate law have exponents equal to their stoichiometric coefficients in the balanced equation for the chemical reaction.*

Question 4 requires students to write the rate law given the order of reaction with respect to the reactants. A small portion of students selecting Q4-AA (CR(TA) = 3.89 and CR(TR) = 3.56) demonstrates that these students are not aware that the rate law must be determined experimentally. A possible reason for this mistake is that examples of rate laws given in chemical kinetics' teaching often align with the coefficients in the balanced chemical equation. This could lead to the conclusion that the exponents in the rate law expression are directly obtained from the coefficients of the reactants in the chemical equation. This misconception has previously been observed.[5,11,14,15] More selective choice of examples of rate laws and associated chemical equations in chemical kinetics' teaching might help avoid this confusion.

2. *The rate law is derived in the same way as the equilibrium coefficient.*

The proportion of students (14%) who wrongly selected Q4-CB (CR(TA) = 4.34 and CR(TR) = 3.74) confirmed this as a *genuine* misconception. Answer C assumes that the rate law is derived in the same way as the equilibrium constant from a chemical equation and is based on the law of mass action. This misconception is reinforced by students' responses to Q17-AC (CR(TA) = 4.06 and CR(TR) = 3.85) in which Answer A is obtained by deriving the rate law from the stoichiometric equation. Reason C supports this answer, i.e. *the rate law is obtained directly from the overall reaction equation*.

Also in Question 17, 8% students, with a CR(TA) = 3.58 and CR(TR) = 3.38, believed that for the reaction $NO_2(g) + CO(g) \rightarrow NO(g) + CO_2(g)$ the rate is given by: *Rate* $= k\,\frac{[NO]\,[CO_2]}{[NO_2][CO]}$, (answer D) with the reason is that "*the rate law is obtained directly from the overall reaction equation*" (reason C). A smaller proportion chose D as their reason (*the rate law is derived from the law of mass action)* (CR(TR) = 3.00). This is a more logical reason to fit with the incorrect answer D than reason C but is the wrong reason for the correct answer. It is possible that some students are not familiar with the term 'law of mass action' and so avoided this reason. This reinforces the findings of Voska & Heikkinen[29] who found students often confuse the law of mass action with the rate law.

3. *The rate law in a multi-step reaction is obtained solely from the slow step.*

Question 12 requires students to select the correct answer for the rate law in a two-step reaction with an initial fast step, which is an equilibrium reaction, followed by a slow step. 7.16% students selecting Q12-AA (CR(TA) = 3.96 and CR(TR) = 3.96) have ignored the fast step in this multi-step mechanism, in which the intermediate 'I' is produced. A small portion of students with high confidence selected Q12-BC (CR(TA) = 4.30 and CR(TR) = 3.50) and applied the law of mass action to the slow step of the equation. This relatively high confidence rating in the A tier suggests students were quite comfortable with their answers. 11.04% of students selecting Q12-BA (CR(TA) = 3.92, CR(TR) = 3.62) stated that the rate law was obtained from the slow step in the mechanism, having ignored the prior equilibrium fast step. Other students selecting Q12-BB stated that the rate law is obtained from the fast step in the reaction, despite their answer involving reactants and products of the slow step. This could be because the procedure for deriving the rate law from a multi-step mechanism is often covered towards the end of a course on chemical kinetics, so possibly students had little time to internalise the material.

3. 3. The Change in the Concentration of a Reactant or a Product with Time

1. *The rate of a reaction can only be expressed in terms of concentrations of reactants.*

Question 20 asks students to derive an expression for the rate of a chemical reaction in terms of the rate of disappearance of reactants or products. Students are given data about the rate of disappearance of the only reactant, N_2O_5, and have to select one correct equation that will represent the rate at which the reaction is proceeding. 10% of students selected Q20-AC (CR(TA) = 4.03 and CR(TR) = 3.48), even though this answer showed that N_2O_5 is being formed and is not disappearing. Only very few students (2.00%) were able to identify both the correct expression for the rate of reaction and the correct reason (Q20-CF) with a strong understanding as demonstrated by the high CR(TA) and CR(TB) with 4.33 for each. This involved working out the relationship between the rate of disappearance of N_2O_5 and the rate of formation of O_2 and using the appropriate sign from the stoichiometric equation.

3. 4. Relationship Between Concentration and Rate

1. *Inability to recognise the impact of a change in concentration of a reactant that is zero-order upon the reaction rate*

In Q5 students are told that the reaction is zero-order with respect to one of the reactants, CO, and second-order with respect to the other, NO_2. They have all the information to allow them to determine the rate law. Using this rate law, students were asked to predict the effect of changing the concentration of the second-order reactant, NO_2, on the rate. Some students (7%) answered that the rate would stay the same because the order with respect to one reactant (CO) is zero (Q5-DD) with CR(TA) of 3.91 and CR(TR) of 3.82). Although only a small proportion of students chose this answer/reason combination, they had a reasonably high confidence in their response and so this is considered a *genuine* misconception. This finding has been reported by Cakmakci[3] and Kirik & Boz.[6]

2. *When the concentration of two reactants in an experiment is the same a higher reaction rate is obtained because the collision ratio of molecules is more favourable.*

This *genuine* misconception was shown by 5% students answering Question 6 who selected Q6-CB with CR(TA) of 4.00 and CR(TR) of 3.59. This assumption may appear to be scientifically logical to students assuming a single-step mechanism. However, this reasoning ignores the influence of the rate-determining step upon the rate of reaction therefore students selecting this combination demonstrate a reasonable understanding of kinetic theory but not of reaction mechanisms.

3. *A higher reaction rate is obtained when the concentration of the second-order reactant is the greatest.*

This answer and reason combination was selected by a large proportion of students (24%) who answered Q6-AA with a relatively high confidence rating of CR(TA) of 3.88 and CR(TR) of 3.73 confirming a *genuine* misconception. It is likely that these students failed to apply the appropriate rate law to the concentrations of both reactants in reaction A-D and assumed that the highest concentration of the second-order reactant would maximise the rate. Alternatively, the wrong results could have been obtained by a mathematical error, although the high percentage of students selecting this incorrect answer and related reason would suggest this is a *genuine* misconception.

4. *Reaction rate always increases/decreases with time as a reaction proceeds.*

For question 19 the hypothetical reaction G → H is presented in Figure 2 in which each blue sphere represents 0.2 moles of G and each red sphere represents 0.2 moles of H and the container has a volume of 1.00 L. Students were asked to predict the number of moles of G and H remaining after an intermediate length of time, after working out the rate of disappearance of G from the picture given. Calculation of the average rate during the two time periods shows that it is constant and so the reaction is zero order and reason C is the correct reason.

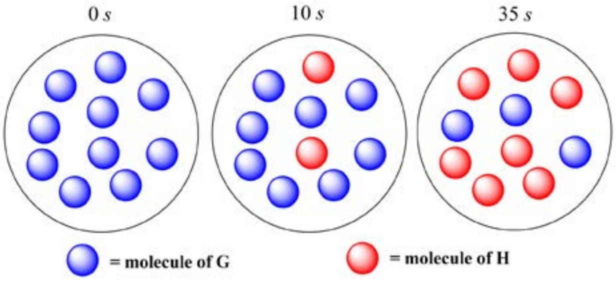


Figure 2. Pictorial representation in Q19

The belief that reaction rate increases with time in this reaction, as shown by students answering Q19-BA (CR(TA) = 3.89 and CR(TR) = 3.44), can be classed as a *genuine* misconception. Previous work has reported that students believe, for example, reaction rate increases to a maximum value, remains constant at that value, and then decreases to zero.[5,6] Others have reported the alternative conception that an increase in concentration of a reactant always increases the reaction rate.[10,12,15]

3. 5. Reaction Half-life and Successive Half-lives

1. *The decrease in mass of a sample is constant for each successive half-life.*

Question 1 is a relatively straightforward question relating to half-life during first-order radioactive decay. 5.1% students had the WAWR combination of Q1-CC with CR(TA) = 4.12 and CR(TR) = 3.65 inferring a *genuine* misconception that the mass change of the sample is constant for each successive half-life. To obtain C students must misinterpret or misread the question and assume that the half-life of the reaction is 10 minutes. The spread of answers and reasons in this question demonstrates a general lack of clarity in the understanding of half-life.

2. The value for the half-life of a reaction is always constant.

Question 3 uses a pictorial representation and requires students to determine the time at which the concentration of NO_2 has further dropped by a half, given the number of molecules of NO_2, NO and O_2. Students are told in the question that the reaction is second order. However, the most popular WAWR combination is Q3-BB (CR(TA) = 4.16 and CR(TR) = 3.91) obtained by assuming this is a first-order reaction. The CR value demonstrates that students are familiar with the concept of a constant half-life for a first-order reaction but are unaware that half-life is not always constant. The confidence ratings imply a *strong* misconception.

Question 11 is deliberately analogous to question 3 except the data are presented textually with information given about the pressure of NO_2 rather than about the number of moles. Again, 16% of students (CR(TA) = 3.83 and CR(TR) = 3.64) selected Q11-BB assuming that the reaction has first-order kinetics and the value of half-life is a constant. This *genuine* misconception demonstrates that students are generally familiar with the half-life of first-order reactions and students often apply the concept of constant half-life to reactions of other orders.

3. 6. Catalysis and Activation Energy

1. Dependence of rate of reaction on activation energy

Question 9 tested students' understanding of the relationship between rate of reaction and temperature given the standard Boltzmann plot showing the distribution of energies of molecules in the same reaction at two different temperatures. The activation energy of the reaction was marked on the x axis as in Figure 3. Students were asked to select the correct statement that describes the rate of reaction at different temperatures. A small proportion of students (4%) chose Q9-AD (CR(TA) = 3.92 and CR(TR) = 3.67) stating that the reason for the higher rate of Y is that the higher temperature results in a higher activation energy. This misunderstanding was also reported by Yalcinkaya et al.[7] Other students (5%) stated that reaction X has a higher rate than reaction Y and chose as their reason that reaction X has the higher activation energy (Q9-AA, CR(TA) = 4.00 and CR(TR) = 3.38) although the plot clearly shows that the activation energy for each reaction is the same. This finding contradicts the one revealed by Kolomuc & Tekin[9] in their survey of chemistry teachers who reported that an increase in temperature decreases the activation energy and so allows for an increase in reaction rate.

The students in our study argued that reaction X (Figure 3) has a higher reaction rate because it has a higher activation energy, although the plot shows that the activation energy in each reaction is the same. The explanation for this genuine misconception could be due to these students failing to correctly interpret the Boltzmann plot given in the question. The diagram is a standard one that commonly appears in textbooks on the topic. However, Justi & Gilbert[30] have asserted that teachers often present this diagram without providing an explanation as to the influence of temperature on reaction rate. Similar research published by Orgill & Crippen[31] explored the manner in which first semester general chemistry students interpreted diagrams when solving questions about electromagnetic radiation. They found that most students avoided using the energy level diagram provided when calculating the wavelength of emitted radiation and preferred to plug figures into the Rydberg equation.

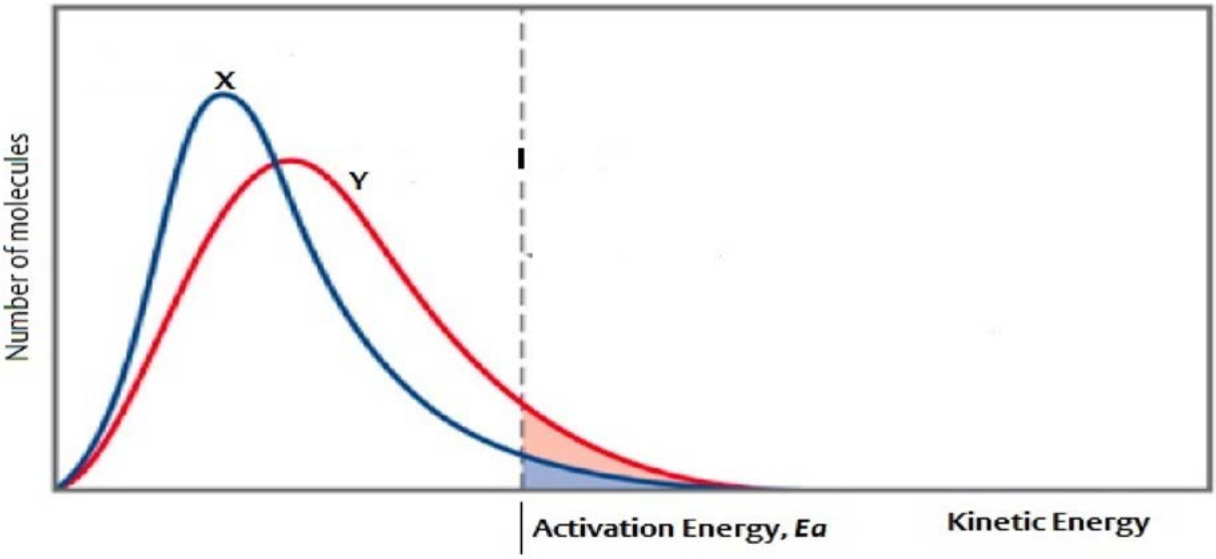


Figure 3. The Boltzmann distribution curves representing reactions of X and Y in Q9

2. An exothermic reaction is the slowest reaction.

Question 10 required students to use plots of energy profiles for four reactions carried out at the same temperature to determine the reaction with the slowest rate. Some of the possible distractors in the reason tier involved statements concerning exothermic and endothermic reaction profiles, an area that has been explored previously in the literature. To correctly answer this question respondents were expected to calculate the activation energy (kJ mol^{-1}) from the y axis values where the scales and maximum values of y were different for each plot.

A small proportion of students chose their answer based on reason A that the reaction with the slowest rate 'has the highest energy in its transition state'. Reaction A actually has the highest energy transition state but not the highest activation energy. The answer that corresponds with this reason is answer A (Q10-AA, CR(TA) = 3.40 and CR(TR) = 3.60). Some students chose the correct answer (C) but gave the wrong reason (A) indicating that these students also confused the activation energy and the energy of the transition state, or did not realise they should use values from the plots to determine the energies. This concurs with the finding of [32] who reported students of this topic may confuse an interval on a graph defined by two points with a single point – e.g. activation energy difference with actual potential energy.

Some students with CR(TA) of 3.44 and CR(TR) of 4.00 thought that the slowest reaction would be an exothermic reaction. Two exothermic reactions were depicted in the question (A and D). Almost the same number of students selected Q10-AE with a similar confidence rating. A small portion of the total students thought that the slowest reaction would be an exothermic reaction but chose an endothermic profile as their answer. In the literature there are both reports of students and teachers believing that exothermic reactions are slower than endothermic ones[3,7,9,33] and conversely that endothermic reactions are slower than exothermic ones.[3,6,7,14,33] For Question, Some students selected Q14-CD (CR(TA) = 3.57 and CR(TR) = 4.29) and arrived at answer C by subtracting the energy of the products from the energy of the transition state for the catalysed reaction rather than subtracting the energy of the reactants from the energy of the transition state. They also believed that the mechanisms for both reactions are the same.

Question 15 gives a pictorial representation of a two-step reaction scheme in which a set of reactants in the presence of a catalyst is converted to a different set of products. Students are asked to identify the catalyst in the reaction mixture. In the cartoons the correct answer is the only molecule that is present at the start and at the end of the reaction and so should be straightforward to spot.

3% students chose the WAWR combination Q15-BA (CR(TA) = 4.56 and CR(TR) = 4.22) and 6% of students chose Q15-BC (CR(TA) = 3.80 and CR(TR) = 3.90). The molecule depicted in answer B represents a species that is unchanged after the first step of the reaction but not present at the end of the reaction. It is possible that students choosing answer B assumed that the catalyst was the molecule that was unchanged *after the first step*. They chose reason C; *a catalyst increases the rate without being chemically involved in the reaction* despite the fact that all the species depicted are changed at some point during the reaction mechanism and so there is no answer that fits this reason.

3. 7. Factors that Affect Students' Misconceptions

This study suggests that students' misconceptions in the understanding of chemical kinetics can be caused by a number of factors including mathematical weakness, carelessness in reading the information in the question, difficulty in interpreting visual information (tables, diagrams,

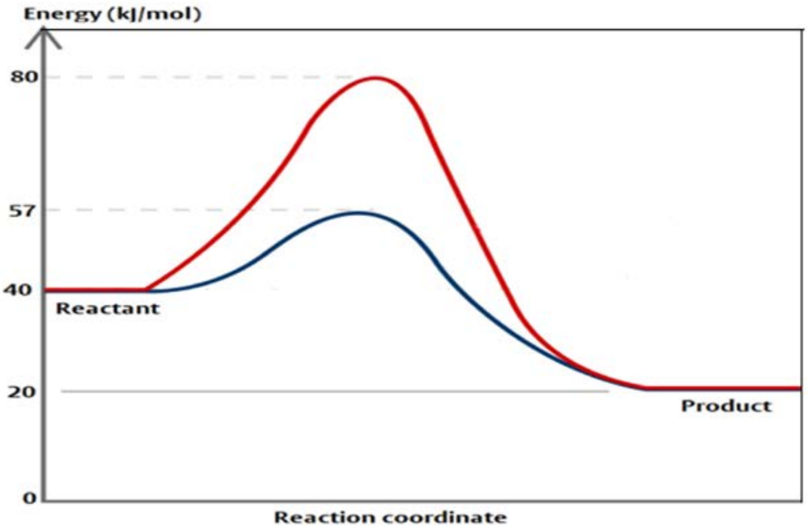


Figure 4. The energy profile describes a catalyzed and an uncatalyzed pathway for a given reaction

graphs etc) and confusion over chemical terminology and vocabulary.

Mathematical difficulties often cause students to introduce errors. In particular, converting a verbal statement to a mathematical/algorithmic operation can create a major challenge for some students. This study also has revealed that many students often answer chemical questions correctly using a formulaic equation by recall and parameter substitution to solve problems without a full understanding of the concepts. This concurs with the previous finding that many first-year students do not understand the significance of equations in chemical kinetics or how to implement the equations to solve a problem[34] even though they may recall or be given the actual equation. The study of Rodrigues et al[35] revealed that strong ability in symbolic and graphical representations reasoning is a profound way to facilitate students in integrating chemistry and mathematical knowledge.

Another factor affecting students' low performance in this study is carelessness in reading and/or interpreting the question. For example, in question 6, many students only focused on the number of molecules of the second-order reactant and ignored the number of molecules of the first-order reactant without performing the required mathematical calculation. In several circumstances, students only focused on the mathematical operation without a sufficient conceptual understanding. For example, in question 20, many students provided the correct mathematical expression for the rate law with respect to a particular reactant but failed to provide a negative or positive sign showing they did not fully understand the meaning of the relationship between change in concentration with time and rate.

Inability to identify relevant information from a diagram, graph or table can indicate poor conceptual understanding and lead to misconceptions. Extracting data from a visual aid requires additional skills besides simply reading textual information. Students must be able to translate visual clues such as points, lines, intervals, gradients, axis titles, units, colours and other representations into chemical meaning which requires good prior explanations and practice. For example, referring to Figure 3 above (question 9), two reactions are represented as X and Y with the same activation energies. However, many students believed that X has a higher rate than Y as they thought X has the lower activation energy. Because the curve shown is lower for X than Y at the value of the activation energy, some students believed that the activation energy for X is lower and the reaction therefore faster.

Difficulty with chemical terminology is another factor that leads to students' misconceptions observed in this study. This difficulty results in confusion between the precise meaning of chemical terms. For instance, students confuse reaction rate with time of reaction, initial rate, average rate, instantaneous rate and rate with respect to a specific reactant, and the terms rate law, rate expression and rate equation.

In many cases students memorise a scientific definition without having an adequate understanding of its conceptual meaning. For example, students correctly remember that half-life is constant in a first-order reaction but then apply this concept incorrectly to zero and second-order reactions. In another similar example students are taught that reaction rate decreases with time and apply this general concept to all reaction types including zero-order reactions. Students correctly argued that the concentration of a reactant at its half-life is a half of its initial concentration. However, when the question was portrayed in a pictorial format, students found it difficult due to their inability to interpret a visual representation. In addition, as has been reported previously, confusion between chemical kinetics and other topics such as chemical equilibrium and thermodynamics is also a cause of students' misconceptions. For example, many students derived the rate law of a reaction by using the stoichiometric equation in the same way as they would derive the equilibrium constant expression.

4. Conclusions

The results of this study point to several findings as summarised below. The FTDICK instrument is a valid instrument for use in investigating first-year students' misconceptions in chemical kinetics. The procedure employed in this study confirms that results obtained by using this four-tier instrument reveal students' *genuine* misconceptions in chemical kinetics. In addition, incorrect classification of a *spurious* misconception as a *genuine* misconception and vice versa can be avoided. If deployed at an appropriate time in the curriculum the instrument can help educators identify students' misconceptions before embarking on chemical kinetics topics at the tertiary level. More targeted and effective teaching can be designed if staff are aware of students' prior-knowledge misconceptions.

Numerous *genuine* misconceptions within chemical kinetics were revealed among first-year chemistry undergraduates. Although some of these misconceptions align with previous results published in the literature novel findings have been revealed in this study. The study has highlighted common misconceptions in the subject area which, if addressed in a timely manner, will help prevent students' developing further difficulties as they embark on their studies in chemical kinetics at the tertiary level.[36]

4. 1. Implications for Teaching Chemical Kinetics

The primary aim of this study is to use the results to inform and improve the quality of teaching and learning in chemical kinetics. Based on the analysis of students' answers and confidence ratings there are several implications for the teaching of chemical kinetics.

Students appear to be familiar with the characteristics of first-order reactions but struggle with the kinetics of reactions with different orders. This can be attributed to several factors. One reason is the content of chemistry textbooks. Several general chemistry textbooks devote the largest page allocation to explaining first-order reaction kinetics and zero and second-order reactions receive little attention. In addition, the concept of first-order reactions involves radioactive decay and this improves their confidence in the topic. More emphasis on different reaction orders and their characteristics would enhance students' understanding in this topic.

Several students were found to believe that the exponents in the rate law expression are directly obtained from the stoichiometric coefficients of the reactants in the chemical equation. A possible reason for this is that examples of rate laws given in chemical kinetics' teaching often align with the coefficients in the balanced equation. To avoid this misconception, teachers should provide varied examples of rate laws in which the exponents in the experimentally determined rate laws are not the same as the coefficients in the chemical equations. This can be reinforced through practical work in which students determine the rate law from experimental data.

To address the misconception that an increase in concentration of a reactant always increases the reaction rate, the word "generally" should be used and emphasised when teaching about factors that affect reaction rate. Meanwhile, to avoid the typical misconception that the reaction rate decreases with time for all reactions, chemistry educators should stress that the term 'zero-order' implies that the rate does not depend upon the concentration and therefore the rate is constant through the reaction and does not change as the concentration of reactant decreases and/or increases.

Teaching strategies that can provide better opportunities for students to develop their reasoning skills such as learning cycle and guided inquiry are highly recommended.[37] Student-centred teaching such as inquiry-based practical chemistry was found to be effective in improving students' understanding of chemical kinetics.[34]

The study also showed that students have difficulty when interpreting visual representations. Therefore, more practice should be given in this area, for example by providing information in graphical or pictorial representations when appropriate. As found in Q13, students' inability to differentiate the energy profiles of exothermic and endothermic reactions could be because many textbooks only present the energy profile for an exothermic reaction. Therefore, parallel presentations of the energy profiles for both endothermic and exothermic reactions is highly recommended[38]. Many recent chemistry textbooks are illustrated by drawings and other pictorial representations in order to help students' reasoning. However, such representations are still limited in the secondary school textbooks in Indonesia. A similar phenomenon was also found in the school textbooks in Greece.[2]

Evidence from this study implies that students need appropriate guidance in interpreting information. The cognitive theory of multimedia learning suggests that conveying a verbal explanation which is accompanied by an appropriate picture rather than just a textual explanation contributes to students' robust understanding.[2] Assessment using diagrams and graphs is recommended to improve this skill. Engaging students with technology for enhanced learning, such as a 3D-model[39,40] could also be a reasonable exercise for teaching and assessing relevant concepts.

As chemical terminology surrounding kinetics is confusing, chemistry educators are advised to provide clear definitions of relevant terms. Some terms have very similar names such as reaction rate and reaction time; rate law, rate expression and rate equation. Educators should ensure that each term is explained carefully to students and sign-post synonyms. Barke et al[36] stated that misconceptions inculcated at school are due to incorrect use and understanding of chemical terminology and scientific language. Even chemistry educators can be lax with language in this area. Confusion that exists between some common everyday words and chemical terminologies is one of the barriers to chemistry teaching[41] and can lead to misconceptions.[42]

Poor mathematical ability may not directly affect students' misconceptions but can lead to weaker understanding and poor performance. However, this issue is clearly a prominent barrier to teaching and learning and should be considered. In Indonesian universities, maths is generally taught to chemistry students as an independent module, distinct from chemical concepts. Students are expected to apply their mathematical knowledge in chemical contexts. In the UK it is more common to provide dedicated 'maths for chemists' modules in an integrated manner in order to support students in performing simple calculations on chemistry topics. This practice should be considered in Indonesian universities, and other education systems where maths is taught separately from chemistry, in order to improve chemistry students' ability in transferring mathematical knowledge to a chemical context. As proposed by another study that the approach to teaching chemistry involving mathematical operation should be reformed.[43]

Students' difficulty in converting verbal statements to mathematical operations and vice versa is another cause of misconceptions. To address this, more practice should be given in this skill rather than providing examples where numbers can simply be slotted into the appropriate equation. Students' mathematical skills, logical thinking and interpreting information from verbal statements and diagrams are all essential elements for success in physical chemistry.[44] It may also be useful for exploring a procedure for mapping students' reasoning process, such as Talanquer's Heuristic Approach, as shown by Karakoyun & Asilturk[45] in acid-base.

4. 2. Limitation of the Study and Future Work

The equal number of Indonesian and UK students hinders a robust comparison of the performance of British and Indonesian students. Also, with only two participant countries, it may not be powerful enough to generalise this study's result internationally. However, it would be prudent to extend the work carried out here to involve students of different nationalities. It would also be instructive to extend the study to further universities in both the UK and Indonesia to obtain a more robust picture of student understanding of chemical kinetics at this level.

A similar four-tier approach is recommended to explore understanding in other physical chemistry topics such as thermodynamics, chemical equilibrium and electrochemistry. Specific areas of organic, inorganic, analytical and biochemistry would also benefit from similar studies. Most importantly, future work should involve using the FTDICK instrument in the teaching of chemical kinetics to empirically evaluate how the instrument can improve the quality of teaching in chemical kinetics at the university level.

Dissemination of the results of this study to chemistry educators and policy makers is essential to enable practitioners, particularly in Indonesia, to design appropriate teaching practices, textbooks and other resources. Agung & Schwartz[46] stated that the limited number of published studies in Indonesia focusing on students' misconceptions in chemistry, in particular, and the sciences in general, may be the reason why educators and policymakers do not take these students' misconceptions into account. Similarly, Gegious et al[2] found that school textbooks in Greece have not been influenced by the results of chemical education studies. Unfortunately, chemistry teachers rarely critically evaluate textbooks which are used in their chemistry classes. As a result, many of these textbooks do not help students to gain a better conceptual understanding.[2]

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Ethical Statement

Approval for the study described was granted by the university ethics board. All students gave informed consent to partake in the study.

Statements and Declarations

We declare that this study has no potential conflicts of interest, including financial funding.

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Povzetek

Namen študije je raziskati napačno razumevanje študentov prvega letnika univerzitetnega študija o kemijski kinetiki z analizo podatkov, pridobljenih s štiristopenjskim diagnostičnim pristopom za kemijsko kinetiko (FTDICK). V tej študiji je sodelovalo 335 študentov prvega letnika kemije z dveh indonezijskih in ene britanske univerze. Opisani postopek je prvi te vrste, ki zagotavlja, da so ta napačna razumevanja resnična. Med študenti prvega letnika študija kemije so se razkrila številna napačna razumevanja na področju kemijske kinetike. Čeprav se mnoga od ugotovljenih napačnih razumevanj ujemajo z rezultati, ki so bili predhodno objavljeni z uporabo drugih pristopov, je bilo odkritih tudi nekaj novih ugotovitev. Ta napačna razumevanja je mogoče pripisati različnim dejavnikom, vključno z matematično šibkostjo, neprevidnostjo in težavami pri razlagi in pridobivanju informacij iz diagramov, grafov in drugih nebesedilnih informacij. Na podlagi rezultatov te študije podajamo nekaj priporočil za izboljšanje učinkovitosti poučevanja kemijske kinetike na tej stopnji.