TURKISH SECONDARY AND UNDERGRADUATE STUDENTS' UNDERSTANDING OF THE EFFECT OF TEMPERATURE ON REACTION RATES

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Abstract

The research reported in this paper is part of a research project aiming to evaluate upper secondary school and undergraduate students' conceptual understanding of chemical kinetics in the light of the aims of the Turkish chemistry curriculum. The study is based on written responses given by 191 upper secondary school students (ages 15-16) and pre-service chemistry teachers (age 17+) to a series of written tasks involving concepts and phenomena in chemical kinetics. Follow-up interviews were also conducted with a number of students in order to probe their understanding in more depth. This paper focuses on the development of students' understanding of the effect of temperature on reaction rates, following relevant teaching, from school to university. In a broad sense, the students following the curriculum made progress from school through university. This progression was different in different areas of chemical kinetics. (1) Changes in the nature of explanations offered by students (descriptive/empirical vs. explanatory/theoretical), and (2) changes in the conceptual content of explanations (e.g. a U-shaped performance curve) offered by students were identified. The results suggest that students' lack of understanding in thermodynamics and chemical equilibrium significantly influences their ideas about chemical kinetics. Some possible implications drawn from the study for teaching and learning chemical kinetics and other related concepts are proposed.

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Introduction

Because chemical kinetics is one of the most fundamental concepts in chemistry, it is regularly taught in both school and university courses in Turkey, as elsewhere (Justi 2002). Though some chemistry topics have been the subject of extensive research (e.g. chemical change and chemical equilibrium), relatively little *empirical* research has been carried out on (1) students' ideas about chemical kinetics, and on (2) how understanding of chemical kinetics changes as students move through the curriculum (Justi 2002, Cakmakci 2005c). Whilst, students experience difficulties in understanding of chemical kinetics both at school (de Vos & Verdonk 1986) and university levels (Lynch 1997), further research is required in order to give insights into the ways in which students conceptualise the domain at school and university levels.

The research reported in this paper is part of a research project aiming to evaluate secondary school and undergraduate students' conceptual understanding of chemical kinetics in the light of the aims of the Turkish chemistry curriculum (Cakmakci, 2005a). In other words, the study aims to find out how effective the curriculum has been in meeting its aims in terms of students' understanding. If it is not being effective, this study could identify in what aspects it is not being effective so that the data can be interpreted in terms of the content structure of the domain, of the structure of the curriculum, and of the materials used during teaching (e.g. textbooks, examinations papers). As a consequence, relative strength and weaknesses of the education system in the area of chemical kinetics can be characterised and the results can improve understanding of the outcomes of the chemistry education at school and university. Such information can inform decisions about where and how improvements to the chemistry curriculum can be made.

This paper focuses on the development[2] of students' understanding of the effect of temperature on reaction rate, following relevant teaching, from school to university.

Design and methodology

This cross-sectional study is based mainly on written responses given by school and undergraduate students to a series of written tasks, termed 'probes', involving concepts and phenomena in chemical kinetics. In order to evaluate the effectiveness of the curriculum in meeting its aims (in the area of chemical kinetics), conceptually *and* phenomenologically framed probes were designed and deployed. Conceptually framed probes aim to investigate how well particular concepts that have been taught, have been understood by students (i.e. eliciting students' propositional knowledge). Phenomenologically framed probes aim to explore which knowledge students use when given minimal contextual support within the probes, and to find out how appropriately they use their knowledge in different phenomena or situations where the relevant concepts are not presented (i.e. eliciting students' knowledge-in-action) (Driver & Erickson 1983). The sample for the main study included 108 secondary school students (Grade 10, ages 15-16) in three classes from two different schools, 48

[2] We use the word 'development' to refer to changes in the ways in which students reason in the field of chemical kinetics. No implication about cognitive development is intended.

first-year (age 17+), and 35 third-year (age 19+) pre-service chemistry teachers. Follow-up interviews were also conducted with 24 students in order to probe their understanding in more depth and to check for appropriate interpretation of the written responses. This sub-sample was chosen to represent diversity in responses to the written probes.

All school students who participated in this study majored in mathematics and science. Chemical kinetics is first introduced in the Turkish curriculum in the upper secondary school (ages 15-16). The topic is taught again in detail in the first year and in the third year of a five-year pre-service chemistry teacher-training programme.

Probes

Students' ideas about the effect of temperature on reaction rates were elicited throughout their responses on two contextually different probes (see the appendix). The 'nitrogen monoxide probe', framed in the language of chemical kinetics, asked students how a rise in temperature would affect the rate of the following reaction: $2NO_{(g)} \xrightarrow{Pt} N_{2\,(g)} + O_{2\,(g)}$ $\Delta H<0$ (Exothermic). The 'rusty water pipe probe' which is framed in terms of the phenomenon of rusting required students to explain why the outside of the hot water pipe would rust more than the outside of the cold water pipe.

Data analysis

A coding scheme was developed by reviewing students' responses in interviews and to written probes, and by identifying common ideas and ways of explanation. The coding scheme was thus developed from students' responses rather than being based, for example, on normative science. Three main categories of responses were identified and used in the reporting of results:

(1) Descriptive/empirical (macroscopic modelling),
(2) Explanatory/theoretical (particulate and/or mathematical modelling), and
(3) All other responses (see figure 1)[3] .

The category termed *descriptive/empirical (macroscopic modelling)*[4] is descriptive in nature. This phrase refers to knowledge of what happens; interpreting the phenomenon in terms of what might be perceived (i.e. at a macroscopic, phenomenological level) but not referring to unseen entities and processes –such as interaction of particles/ molecules/ ions– or underlying mechanisms to account for the phenomenon. In some cases, students' responses are expressed mainly using everyday language or they include tautological restatements of available information in the task.

[3] This framework reflects others used in the literature, such as Logan's (1984) distinction between the empirical and theoretical level of chemistry, Johnstone's (1991) distinction between macroscopic, sub-microscopic, and symbolic level of chemistry, and Tiberghien's (2000) distinction between the world of objects/events and the world of theories/models.
[4] For the complete characteristics of these categories, see Cakmakci (2005b).

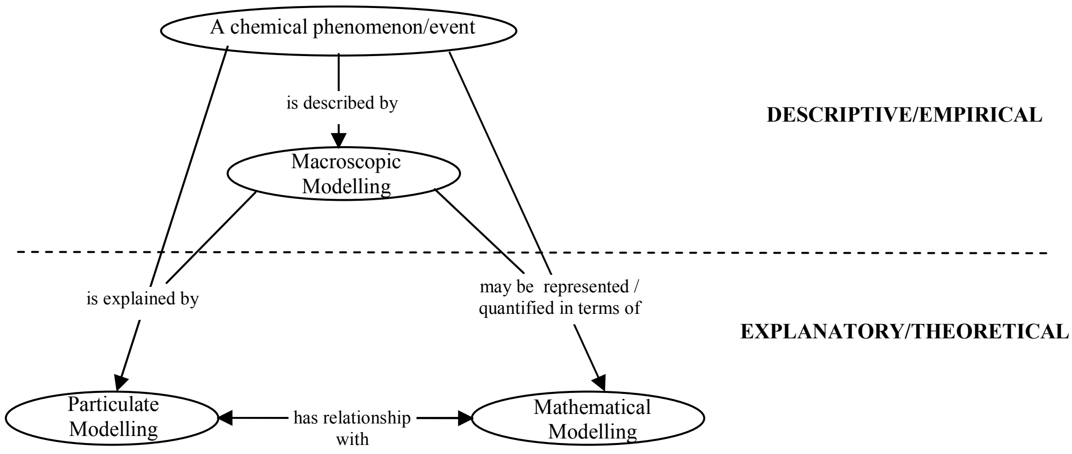


Figure 1. *The relationship between chemical phenomena/events and theories/models (A framework for analysing students' explanations of chemical kinetics)*

The category termed *explanatory/theoretical (particulate and/or mathematical modelling)* incorporates responses in which students use some form of theoretical model or causal mechanism to account for the phenomenon/event. The causal mechanism proposed might involve a chain of events between variables or the evocation of formally defined theoretical constituents in chemistry. Explanation goes beyond the phenomenon/event by drawing upon theoretical entities that are not observable in the phenomenon itself. This category includes two subcategories: particulate modelling and mathematical modelling. The subcategory termed *particulate modelling* incorporates those responses in which students use corpuscular models such as interaction of particles/ ions/ atoms/ molecules, or use the principles of the collision or transition-state model in their reasoning. The other subcategory, termed *mathematical modelling* is allocated to cases where justification involves algebra, diagrams, mathematical formulae (e.g. reaction rate=k. $[A]^m$) or equations (e.g. $2Fe_{(s)} + O_{2\,(g)} \rightarrow 2FeO_{(s)}$).

The category, termed all other responses, is allocated for incomprehensible responses or in cases where there is no response given in any part of the probe.

Results and discussion

Results of the rust water pipe probe

The rusty water pipe probe aims to explore students' ability to deploy chemical knowledge within a relevant context where the stimuli presented to students are an everyday chemical phenomenon rather than the concepts used in chemistry to explain it. The intention was to investigate in what way students analyse the phenomenon (descriptive/empirical vs. explanatory/theoretical) and to find out how appropriately they use their scientific knowledge and understanding when minimal contextual support is given within the probe. It was found that there is a statistically significant difference between school and undergraduate students' reasoning in that the reasoning based on theoretical models gradually increased from school to university level (χ^2=37.419, df=2, p<0.01) (see figure 2), and undergraduates' responses were more likely to have scientifically correct ideas. Around half of the school students interpreted the phenomenon in terms of its observable features and did not make links between chemical concepts and the chemical phenomenon. Many school students did not invoke some scientific terms or principles such as atoms, molecules or the principles of the collision model in their explanations (even though they had been emphasised in the chemistry courses), a finding similar to that of Andersson (1986). For instance, such students might argue that "heat destroys substances" or "hot water destroys/wears out/tarnishes the water pipe". These students seemed to interpret the phenomenon by using everyday terms and language. In some cases, students had a preference for prototypical examples of everyday phenomena or metaphors; for instance, they considered rusting as something like decay. Here is an example:

> *Heat results in rust. Temperature destroys the structure of some substances. That is why we keep our foods in the fridge. Foods spoil very easily when left out at room temperature.* [Sa-D-15]

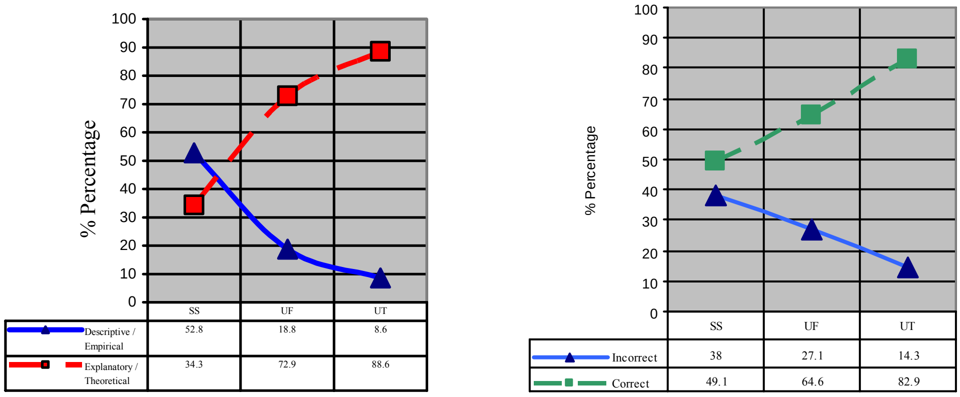
Nevertheless, from school to university, there was, not surprisingly, a considerable progression in the number of students who justified their answers by referring to a theoretical model. Around 24% of the SS[5], half of the UF, and 74% of the UT appropriately attributed a theoretical model to the phenomenon. A few students used theoretical models inappropriately in the given situation. For instance, their responses centred on the ideas that an increase in temperature increases the rate of endothermic reactions and that oxidation/rusting was seen as an endothermic reaction.

> *…The reaction between the water pipe and oxygen from its surroundings is an endothermic reaction which needs energy to proceed. Due to a higher heat, it reacts easily with oxygen. Since the reaction rate is directly proportional to temperature, the hot water pipe will rust more than the cold water pipe.* [UF-D-05]

> *Oxidation is an endothermic reaction. $2Fe + O_2 + Heat \rightarrow 2FeO$. This reaction needs energy to occur; therefore, the hot water pipe gets rustier than the cold water pipe.* [UF-D-02]

Interviews with students revealed that they often inappropriately attribute a relationship between thermodynamic and kinetic factors or they lacked knowledge of fundamental thermodynamic concepts. They believed that heat/energy is needed to initiate an endothermic reaction, but it is not needed for an exothermic reaction. In other words, they thought an endothermic reaction cannot be spontaneous, as reported in earlier studies on students' ideas about thermodynamics (Johnstone et al. 1977, Sozbilir 2002).

[5] 'SS' refers to secondary school students and 'UF' and 'UT' refer to university first year and university third year students respectively.



Uncodeable	13	8.3	2.9
Total %	100	100	100

Figure 2. *Percentage of responses to the rusty water pipe probe*

Results of the nitrogen monoxide probe

The nitrogen monoxide probe included sub questions, and one of which asked students how a rise in temperature would affect an exothermic reaction. When students dealt with the probe, around 71% of the school and 60% of the university third year students' responses included correct ideas, nevertheless only 23% of the university first year students' responses included correct ideas. When results (the "correct answers") were graphed, a *U-shaped performance curve* appeared (see figures 3). As students' responses were examined, it was apparent that school and undergraduate students' responses were different in that the reasoning based on theoretical models significantly increased from school to university level (χ^2=35.491, df=2, p<0.01). Though the majority of the SS (71%) correctly predicted how a change would affect the reaction rates, they mainly justified their claims in terms of macroscopic modelling. By contrast, most of the undergraduates used various theoretical models in their responses. Interestingly, although majority of the university first year students gave explanations based on theoretical models, only a small number of them had achieved a correct answer. Perhaps surprisingly, only 6% of the UF used theoretical models appropriately. Nevertheless, the proportion of students which correctly used a theoretical model in their explanations significantly increased from university first year to third year.

As reported above, many university first year students could not use theoretical models appropriately. For instance, such students applied Le Chatelier's Principle to explain the effect of temperature on the reaction rate (c.f. Quilez & Solaz 1995), and argued that "a rise in temperature decreases the rate of exothermic reactions". Here is an example:

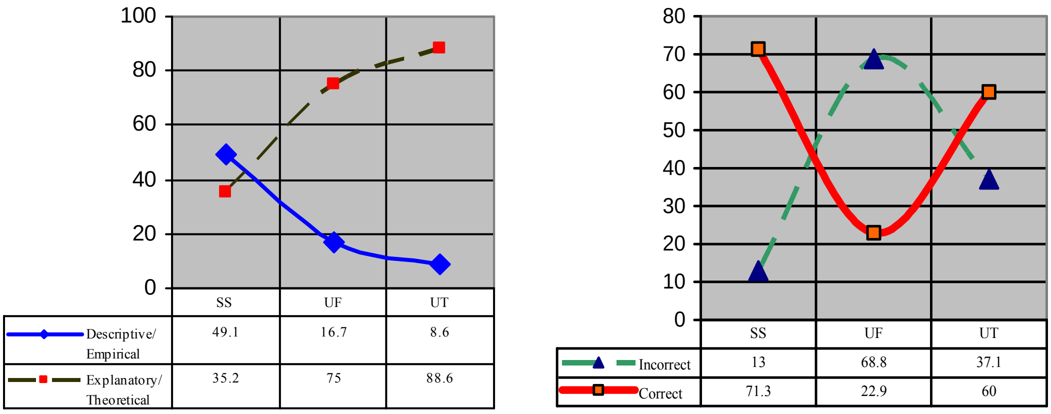
> *Since the reaction is an exothermic reaction, an increase in temperature would affect opposite side and it decreases the reaction rate. The reaction gives out heat; therefore a rise in temperature would decrease the reaction rate*. [UT-D-17]

In addition, as reported earlier in the rusty water pipe probe, confusion between kinetic and thermodynamics was seen from students' responses. For example, they believed that a rise in temperature would not affect the rate of exothermic reactions.

> *Since the reaction gives out heat, increased temperature would not affect the reaction rate. However, if a reaction took heat* [from its surroundings]*; the reaction rate would increase with temperature. Because a rise in temperature increases the rate of a reaction that takes in heat.* [UF-D-17]

> *I don't think an increase in temperature would affect the rate of this reaction, because it is an exothermic reaction. While it gives off heat to its surroundings, temperature* [changes] *does not affect this reaction* [rate]. [UF-D-02]

The underlying idea behind those responses was probably that exothermic reactions release energy; therefore they do not need energy to proceed and a rise in temperature would not affect the reaction rate. Students seemed to confuse the chemical kinetic concepts with thermodynamic concepts. Indeed, there is considerable evidence to show that students believe that endothermic reactions could not be spontaneous; however exothermic reactions could be spontaneous (e.g. Johnstone et al. 1977). Alternatively, the conceptual difficulties would arise due to a misapplication of Le Chatelier's principle.



Uncodeable	15.7	8.3	2.8
Total %	100	100	100

Figure 3. *Percentage of responses to the nitrogen monoxide probe*

The U-shaped change has variously thought to represent outcomes of teaching, performance, or development (Strauss & Stavy, 1982). For the current study it seemed that teaching had a negative effect on university first year students. It seems that the U-shaped performance is mainly a product of students' lack of knowledge about the appropriate use of Le Chatelier's principle. It ought to be underlined that the U-shaped performance curve does not represent a natural or necessary pattern; rather it occurs as a result of misapplications of some rules, formulae, principles or variables which are embodied in a task. The drop and subsequent rise in performance and what is underlying it would inform designing teaching to overcome these difficulties.

Perhaps, those patterns are inevitable when students do not conceptualise the domain. Students may need some time in order to understand, apply and reflect their knowledge and understandings in this area. In that respect, revisiting concepts in the curriculum over a period of time and within closely related concepts would help students' understanding.

Although, individual students' responses to these two probes were not compared in a systematic way, the general picture showed that students' ideas about the effect of temperature on reaction rates are not secure and depend to some extent on the format and contextual features of the probes presented. Subsequently, the results demonstrated that regardless of educational level, there was little evidence showing that students offered explanations with a commitment to generalisability across these two probes. Here is an example:

A student's response to the rusty water pipe probe:

> *….This is an oxidation reaction. A rise in temperature increases reaction rate. When temperature is raised, thermal motion of molecules will increase and they will reach the activation energy more quickly.* [UT-D-19]

The same student's response to the nitrogen monoxide probe:

> *Since this is an exothermic reaction, when we increase temperature, the reaction rate will decrease*. [UT-D-19]

Although this university third year student responds to the 'rusty water pipe probe' with a generalised statement which is scientifically correct: "A rise in temperature increases the reaction rate", she makes a scientifically incorrect argument for the 'nitrogen monoxide probe'.

Conclusions and educational implications

In this paper we have discussed the development of Turkish students' understanding of the effect of temperature on reaction rates, following relevant teaching, from upper secondary to university level. In a broad sense, the students following the curriculum made progress from secondary through university level. This progression was different in different areas of chemical kinetics. (1) Changes in the nature of explanations offered by students (descriptive/empirical vs. explanatory/theoretical), and (2) changes in the conceptual content of explanations (e.g. a U-shaped performance curve) offered by students were identified. We found development in forms of justification used across the educational levels, with school students tending to justify their claims by simple prototypical examples or by drawing upon or taken for granted everyday knowledge or by tautological restatements of available information in the tasks. On the other hand, university students were more likely to use some form of theoretical model or causal mechanism to account for the event: nevertheless, most of the university first year students could not use them appropriately in the nitrogen monoxide probe.

Many students appeared to focus on giving a correct answer rather than explaining the underlying reasoning. For instance, they merely stated that "a rise in temperature increases the reaction rate" or that "temperature is one of the factors affecting reaction rate; that is why the hot water pipe gets more rust". One of the reasons might be that the curriculum, classroom activities and assessment (including in the Student Selection Examination (ÖSS)) focused mainly on recalling definitions and algorithmic problems. Indeed, analysis of the examination questions revealed that many questions tested recalling facts about concepts or tested how to manipulate data to solve problems or tested students' mathematical skills. Phenomenologically framed questions were ignored in the examination questions. Furthermore, an analysis of the scientific knowledge presented in the curriculum (both school and undergraduate curriculum) indicates that in most cases, theoretical models are disconnected from chemical phenomena and everyday practices.

Based on a nomothetic data analysis, a U-shaped performance curve was found from students' responses to the nitrogen monoxide probe. Students' lack of understandings in thermodynamics and chemical equilibrium was identified as a main reason for this pattern. As discussed earlier, students did not make a clear distinction between kinetic and thermodynamic ideas and tried to use thermodynamic ideas to explain the kinetic of a reaction: in some cases they confused some concepts in kinetics and chemical equilibria. On the one hand, thermodynamics is about how stable things are in one state versus another, on the other hand kinetics is about how quickly or slowly species react and is about the progress of a chemical reaction. From a student's intuitive viewpoint, it is possible to confuse thermodynamic quantities like Gibbs free energy with kinetics ones like activation energy. One of the reasons would be that these concepts were often taught separately (e.g. some concepts in kinetics and thermodynamics such as activation energy, enthalpy, spontaneity, entropy, free energy, the notion of exothermic and endothermic reactions), and that the relationships or the differences between those concepts were not specified or ignored in the curriculum (as observed by Viennot (2001) in other contexts). Thus, students failed to move between several concepts/domains. Without being explicitly introduced the relationships between some concepts in kinetics, thermodynamics and chemical equilibria, students would have conceptual difficulties in moving between them. We suggest that it might be helpful to emphasise the distinctions between these concepts and to treat some of the components together. Specifically, the results suggest that the limitations of Le Chatelier's Principle deserve attention during teaching (c.f. Quilez & Solaz 1995) and its relationship to kinetic arguments should be shown more clearly in the curriculum. It should be emphasised that the application of Le Chatelier's principle to chemical kinetics is completely wrong.

Understanding of chemical kinetics requires an integrated conceptual understanding of some fundamental ideas: the particulate nature of matter, the kinetic molecular theory and dynamic aspects of chemical reactions (Justi, 2002). We believe it would be useful to treat closely related concepts of chemistry together. In other words, during teaching the teacher (and the curriculum) should help students to move back and forth in order to make links between different concepts introduced to them through teaching. The teacher should encourage students to bring together knowledge of different areas of chemistry and to relate to each other. In conclusion, the instructional strategies need to put more emphasis on how concepts are interconnected so that students will understand the links between them.

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Appendix

Rusty water pipe probe: (adapted from the study by Andersson (1986)).

When a house was newly built both the hot and the cold water pipes in the kitchen were shiny. After a while, the **outside of these pipes** had become dull and rusty (covered with a thin, brown coating). The outside of the hot water pipe was more rusty than the outside of the cold water pipe.

Explain why the **outside** of the hot water pipe was **more rusty** than the **outside** of the cold water pipe. Please give as much detail as you can!

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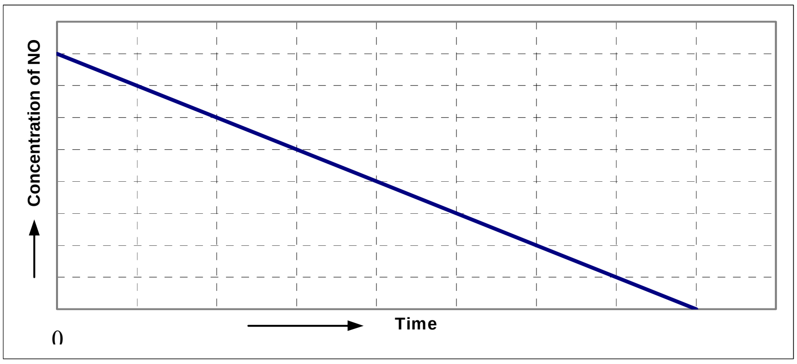
Nitrogen monoxide probe:

Some scientists did an experiment to find out the order of the reaction below:

$$2NO_{(g)} \xrightarrow{Pt} N_{2(g)} + O_{2(g)} \qquad \textbf{ΔH ‹ 0 (Exothermic)}$$

They measured the concentration of nitrogen monoxide (NO) regularly over time.

The graph below shows how the **concentration of NO** changes as time passes.



After interpreting the graph, the scientists concluded that the reaction is **zero order** with respect to ‘NO’ and thus the rate expression for the reaction is: $\mathbf{r_{NO} = k\,[NO]^0 = k}$

a) How do you think the graph supports their conclusions? Explain your answer as fully as you can.

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Explain how the following conditions would affect the reaction rate. **Please give reasons for your answer.**

b) Increasing temperature of the reaction

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Notes: *This paper only focuses on the students’ responses on the sub-question-b (How would an increase in temperature affect the reaction rate?).*