Students' Misconceptions in Chemical Equilibria and Suggestions for Improved Instruction

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Abstract

An investigation was conducted into the common misconceptions in chemical equilibria, adopted by a sample of UK secondary school students. These included the characteristics of a dynamic equilibrium, the nature of the reactants and products at equilibrium, as well as the effect of conditions and catalyst on equilibrium. Suggestions for improved teaching were obtained from the students. These included ensuring a clear and comprehensive delivery of basic principles, more or better use of practical demonstrations where appropriate, and use of practice questions. Further research around these suggestions could investigate the value of consulting students' views and ideas in addressing their misconceptions, to ultimately improve overall conceptual understanding in instruction.

Introduction

Misconceptions, in the field of science, can be defined as beliefs that contradict accepted scientific theories (Eryilmaz, 2002). There have been many studies investigating misconceptions adopted by students, exploring what the science-related misconceptions are, why they are developed by the students in the first place, and how they can be addressed (Bahar, 2003; Gilbert & Watts, 1983; Gil-Perez and Carrascosa, 1990; Gurel et al., 2015; Treagust, 1988). It is generally accepted that these misconceptions are adopted by students through their preconceived ideas about scientific principles, making incorrect links according to incomplete or naive prior knowledge, and subsequently bring these into science lessons (Driver & Oldham, 1986; Gil-Perez & Carrascosa, 1990; Hughes et al., 2013; Treagust, 1988). These misconceptions may impede a student's understanding of related scientific principles, in their present and further learning (Gomez-Zwiep, 2008; Goris & Dyrenfurth, 2010; Kallia & Sentance, 2019). There have been several reported studies, investigating how and why changes in teaching, should be used to address students' misconceptions, in science-related fields, and the implications of this research has been heavily investigated.(Gil-Perez & Carrascosa, 1990; Gomez-Zwiep, 2008; Goris & Dyrenfurth, 2010; Hewson, 1981; Longfield, 2009; Sanger & Greenbowe, 2000; Thompson & Logue, 2006).

Chemistry, is a topic that can afford various misconceptions, highlighting the need to investigate them in greater detail to ultimately find ways to address them through teaching and correct false ideas and improve instruction (Mulford & Robinson, 2002). Chemical equilibria is a topic that was voted by a sample of chemistry teachers as the most difficult chemical topic to grasp (Finley et al., 1982). Chemical equilibria has therefore formed the basis of many studies investigating misconceptions, specifically regarding students in the later stages of secondary education, or even at undergraduate level (Kind, 2004; Nakhleh, 1992; Gorodetsky & Gussarsky, 1986; Satriana et al., 2018; Karpudewan et al., 2015; Geban et al., 2000; Bergquist & Heikkinen, 1990; Hackling & Garnett, 1985; Maskill & Cachapuz, 1989; Banerjee, 1991; Satriana et al., 2018). For example, investigations into misconceptions concerning the rate of reaction at equilibrium, Le Chatelier's Principle, as well as characteristics of a dynamic equilibrium have been shown to be challenging for students in instruction and thus form the source a range of misconceptions, from reversibility to the implications of reactant or product concentration (Akkus¸ et al., 2003; Azizoglu et al., 2006; Banerjee, 1991; Cheung, 2009; Gorodetsky and Gussarsky, 1986; Hackling and Garnett, 1985; Kind, 2004; Quilez-Pardo and Solaz-Portoles, 1995; Treptow, 1980).

In aims to address misconceptions in chemical equilibria, a few studies have examined the success of various teaching strategies (Cheung et al., 2009; Maia & Justi, 2009; Quilez-Pardo & Solaz-Portoles, 1995a; Harrison & De Jong, 2005; van Driel & Graber, 2002; Pekmez, 2010; Olney, 1988; Johnstone et al., 1977; Piquette & Heikkinen, 2005; Özmen, 2007; Bilgin & Geban, 2006). These studies have investigated teaching techniques such as: use of analogies and metaphors; cooperative learning; various analogical models; as well as a number of conceptual change strategies, all in attempts to challenge students' existing misconceptions, give evidence and an explanation as to why their conceptions are incorrect, to then cause students to then readily adopted the plausible and scientifically accepted conception, now supported by their new found understanding (Bilgin and Geban, 2006; Harrison and De Jong, 2005; Hewson, 1981; Johnstone et al., 1977; Olney, 1988; Özmen, 2007; Pekmez, 2010; van Driel and Graber, 2002).

Although previous research has uncovered several misconceptions in chemical equilibria, as well as offered a range of methods to address them, this paper investigates an angle which many studies have neglected: the views of the students themselves, as to what they think could benefit their own education through improved instruction. The work describes an investigation, using survey and interview diagnostics, into some of the common misconceptions in chemical equilibria adopted by students studying at GCSE and A-level in the UK, as well as their suggestions for addressing their own misconceptions through improved instruction. (General Certificate of Secondary Education (GCSE) is an academic qualification for subjects undertaken by 14 to 16 year-olds in the UK. The General Certificate of Education Advanced Level (A-level) is an academic qualification for subjects undertaken by 16 to 18 year-olds in the UK.)

Methodology

Research Design and Sample

The research methods for this study combined surveys and interviews. Student participants, which included sixty-three GCSE students (aged 14-16 years) and sixteen A-level students (aged 16-18 years) all from the same private secondary school, were asked to complete an online survey. An interview was conducted with the students' teacher, of eleven years teaching experience to gain their perspective concerning misconceptions and teaching in chemical equilibria.

Before taking part in the survey, the GCSE students had been formally introduced to chemical equilibria that year, and the A-level students had been learning the topic inside the school chemistry course for their third consecutive year.("Ethics approval was granted for this study from the University of Sussex (Reference No: ER/HRR27/1). Each participant was required to read a Participant Information Sheet outlining the study and their involvement, followed by a consent form.)

Instruments

Student participants were emailed a link to an online survey in which they were asked to answer two questions to ascertain; what misconceptions are particularly prominent at each educational stage, and their thoughts as

Statement	Misconception?
The concentration of the reactants and the products are the same, when the reaction is in dynamic equilibrium.	Yes
In a dynamic equilibrium, the rates of the forward and reverse reactions are equal.	No
The temperature in a dynamic equilibrium is always constant.	Yes
A closed system is a feature of a dynamic equilibrium.	Yes
A chemical equilibrium can only exist if the reactants and products are in the same state.	Yes
Once the reaction reaches equilibrium, the reaction has then finished.	Yes
During an equilibrium, the forward and reverse reactions occur simultaneously.	No
Adding a catalyst increases the yield of the product.	Yes
Adding a catalyst increases the rate of both the forward and reverse reactions by the same amount.	No
A catalyst has no effect on the reaction rate at equilibrium	Yes
A catalyst lowers the activation energy of a reaction at equilibrium.	No
An increase in the pressure will shift the equilibrium to the direction which produces fewer moles of gas.	No
Volume doesn't affect the position of the equilibrium.	Yes
None of the above.	-

Table 1: A list of true statements and misconceptions presented to the students

to how teaching could be improved, to avoid misconceptions from developing in the first place. The interview with the students' chemistry teacher was conducted online and consisted of questions focused on these two areas, as well as a discussion around the students' misconceptions following the results.

Results and Discussion

This section is divided into two parts, firstly seeking to gain a better understanding of some of the misconceptions in chemical equilibria adopted by students, and then secondly a discussion regarding suggestions from students around addressing their misconceptions, or how to avoid them from developing in the first place.

Both sections will be supported by data collected in the survey responses and interview with their teacher. It should be noted that all participants were all from the same school and hence using the same chemistry examination board, which limits the study to a particular syllabus. This study was also conducted during the events of the COVID-19 pandemic, which limited both the variety and number of participants screened.

Statement	Misconception	GCSE (63 students)	A-Level (16 students)
“The temperature in a dynamic equilibrium is always constant”	Students associate a dynamic equilibrium with everything being constant, even though temperature can change, while the equilibrium is maintained.	**13 %**	**31 %**
“A closed system is a feature of a dynamic equilibrium”	Students know that a dynamic equilibrium occurs in a closed system but see a closed system as a feature of a reaction being in dynamic equilibrium, in difference to it in reality being a condition that needs to be met in order to achieve the equilibrium	**83 %**	**75 %**
“Once the reaction reaches equilibrium, the reaction has finished”	Students know that a reaction is stable at equilibrium. However, they fail to recognise that reactions are constantly taking place between the reactants and products.	**6 %**	**13 %**

Table 2: The misconceptions associated with the characteristics of a dynamic equilibrium, along with the percentage of students who adopt them.

Misconceptions in Chemical Equilibrium

First, specific misconceptions, as well as overall topic understanding in chemical equilibria seen for students at each stage of education was screened.

The survey asked students: “*Which of the following statements do you agree with? (Note: You can select multiple statements)*”. All students were presented with a list of thirteen statements from Table 1, eight of which are common misconceptions, based on suggestions from the secondary school chemistry teacher, as well as adapted from surrounding literature.(Banerjee, 1991; Bergquist and Heikkinen, 1990; Cakmakci, 2010; Geban et al., 2000; Gorodetsky and Gussarsky, 1986; Hackling and Garnett, 1985; Karpudewan et al., 2015; Maskill and Cachapuz, 1989; Satriana et al., 2018). The tables in this section detail each of these eight misconceptions, along with the percentage of students who agreed with the statement. It was decided that an adoption of specific misconceptions in 1 in 5 (20 %) students would be an appropriate boundary to warrant concern and therefore discussion in this study.

It should be noted that this question, along with the statements, would’ve benefited from being validated through a pilot survey, and that the ambiguity of some of the statements could potentially limit conclusions drawn regarding the elicitation of misconceptions.

The Characteristics of a Dynamic Equilibrium

In the list of thirteen statements, there were three misconceptions related to the characteristics of a dynamic equilibrium, shown in Table 2 above. It was interesting to note the misconception of temperature always being constant at equilibrium, being adopted by 31 % of A-level students, wasn’t observed to the same extent at GCSE (13 %). It’s important to recognise here that the term “always constant” is open to interpretation, and the statement should’ve specified this to be “always constant, regardless of future conditions imposed on the system”. However, the student’s teacher offered another explanation, that at A-level the students will often be quoted a specific temperature

Statement	Misconception	GCSE (63 students)	A-Level (16 Students)
"The concentrations of the reactants and the products are the same, when the reaction is in dynamic equilibrium"	Students are confusing the concentrations of the reactants and products being respectively constant at equilibrium, with their values being exactly equal to each other.	**48 %**	**25 %**
"A chemical equilibrium can only exist if the reactants and products are in the same state"	Students assume that; since a reaction is stable and constant at equilibrium, that both the states of reactants and products must also be uniform.	**10 %**	**44 %**

Table 3: The misconceptions associated with the reactants and products in a dynamic equilibrium, along with the percentage of students who adopt them.

(i.e. a constant temperature) as they know that temperature changes will affect the equilibrium constant Kc. As an extension of this, it's important to note that conceptual knowledge and understanding can diminish if it isn't properly maintained, with variety in examples.(Bahrick, 1979; Custers, 2010; Fensham, 1980; Georghiades, 2000; Özerem, 2012)

The most prominent misconception concerned the characteristics of a dynamic equilibrium. Most of both GCSE (83 %) and A-Level students (75 %) agreed that "*A closed system is a feature of a dynamic equilibrium*". This was a misconception centred around the idea that; a closed system is something that happens as a result of a reaction being in dynamic equilibrium, rather than in fact being a condition that must be met, in order to achieve the equilibrium. Although, the term "feature" is reasonably ambiguous and could have likely led to misinterpretation of the question for some students. Another possible reason for the heavy adoption of this misconception, could perhaps be because the students are regularly exposed to examples of equilibria, where it's stated to be in a closed system, yet they are still confusing the term and how it relates to chemical equilibria. As a result, students perhaps compartmentalise it with the other characteristics and features of a dynamic equilibrium, highlighting the need to address this misconception by providing a clear explanation of the terminology, in order to better explain the nature of the content (Tyson et al., 1999).

The final misconception that a reaction finishes once it reaches equilibrium, while not heavily adopted, could've been more specific that this also includes both observable and non-observable change.

The Reactants and Products in a Dynamic Equilibrium

As show in Table 3 below, nearly half of GCSE students (48 %), as well as 1 in 4 A-level students agreed that "*The concentrations of the reactant and products are the same, when the reaction is in equilibrium*". This misconception is perhaps attributable to students getting confused after learning that, the concentrations of the reactants and products are constant at equilibrium, and then making a false jump to the idea that the concentrations of both are equal. This misconception is also seen in literature, with Hackling et al suggesting this alternative conception is due to confusion, between stoichiometric coefficients and reactant/product concentrations (Hackling & Garnett, 1985; Karpudewan et al., 2015; Satriana et al., 2018).

The Effect of Conditions and Catalyst in an Equilibrium

Statement	Misconception	GCSE (63 Students)	A-Level (16 Students)
"Adding a catalyst increases the yield of the product"	Students know that a catalyst can increase the rate the reaction to achieve completion faster. They fail to notice that only the rate increases and that the yield will be the same regardless of the time it takes to get there.	**40 %**	**19 %**
"A catalyst has no effect on the reaction rate at equilibrium"	Students assume that if the yield of a reaction doesn't change with the introduction of a catalyst, that it has no effect at all.	**3 %**	**13 %**
"Volume doesn't affect the position of the equilibrium"	Students are explicitly taught the effect of temperature, pressure, and concentration on an equilibrium, but can't see how a change in volume will inevitably relate to a change in pressure.	**33 %**	**63 %**

Table 4: The misconceptions associated with the effect of conditions and catalyst in an equilibrium, along with the percentage of students who adopt them

It was surprising to see a considerable number of A-Level students (44 %) agree that "*A chemical equilibrium can only exist if the reactants and products are in the same state*", in difference to only 1 in 10 GCSE students adopting this misconception. Their teacher explained that at A-level the pupils primarily study homogenous equilibria, applying them to Kc/Kp calculations, so many fail to realise that heterogenous systems can still exist, whereas pupils at GCSE will not have considered it in detail, giving them no reason to assume that the reactants and products need to be in the same physical state. A lack of variety in questions and examples, inhibiting conceptual understanding, has been previously noted (Fensham, 1980; Özerem, 2012).

Lastly, Table 4 above displays results for misconceptions related to the effect of conditions and catalyst on the equilibrium. The misconception that more catalyst will increase the product yield, has been adopted by 40 % of GCSE students, as well as nearly 1 in 5 A-level students in this study. This misconception has been previously identified in other studies, with an explanation being that students tend to confuse reaction rate with yield, leading them into adopting a misconception that if a catalyst can increase reaction rate by lowering the activation energy, then it increases the yield of product at the same time because more products can pass through a lower energy barrier (Cakmakci, 2010; Garnett et al., 1995; Gorodetsky and Gussarsky, 1986; Johnstone et al., 1977). If students can appreciate that; a catalyst increases the rate of both forward and reverse reactions, and the concentrations of reactants and products are always constant values in a dynamic equilibrium, they could perhaps recognise that yield isn't a factor that changes in this case of adding more catalyst (Justi, 2002).

It was also interesting to note how many students at both GCSE (33 %) and A-Level (63 %), adopted the misconception that, "*Volume doesn't affect the position of the equilibrium*". Even though confusion around the use and concept of volume has been cited in literature before, this particular misconception does not seem to feature in many previous studies (Bergquist & Heikkinen, 1990). A possible reason why this misconception is so heavily adopted, as well as why we observe an increased adoption at A-level (when Le Chatelier's principle is introduced), could be due to the way the topic is taught. When students are taught the effect of pressure on equilibrium position, and the students fail to connect the relationship to volume, those students may assume that volume has no effect, simply because that specific condition has not been presented to them in examples. This once again stresses the necessity for variety in examples and questions presented to students during instruction (Fensham, 1980; Özerem, 2012). It should be noted that students could perhaps misinterpret this statement to include all-solid/liquid reactions, and the survey should've specified that this only refers to reactions with gaseous components for this misconception.

Addressing Misconceptions Through Teaching

There has been a wide scope of research surrounding addressing misconceptions in chemical equilibria through instruction (Cheung et al., 2009; Maia & Justi, 2009; Quilez-Pardo & Solaz-Portoles, 1995a; Harrison & De Jong, 2005; van Driel & Graber, 2002; Pekmez, 2010; Olney, 1988; Johnstone et al., 1977; Piquette & Heikkinen, 2005; Özmen, 2007; Bilgin & Geban, 2006). However, many studies neglect the views and suggestions from the actual students, as to what they think could benefit their own education.

All students were asked: "*How do you think teaching could be improved to avoid common misconceptions regarding chemical equilibria?*" This question was optional, and responses were received from 59 of the students (45 GCSE students and 12 A-level students), and then grouped together depending on theme. These suggestions discussed below were not trialled for effectiveness in this study, however the use of some of the suggestions have been investigated in other literature referred to below.

Clear and Comprehensive Delivery of Base Concepts (42 %)

Suggestions centred around, teaching the topic slower (17 %), having clearer notes available (10 %), and explaining the concepts in more detail (15 %), all reflecting the challenge students experience grasping difficult concepts, where they need more time and explanation to digest them. Their teacher also commented on the benefits on going back to the basic principles in surrounding topics such as energetics, a topic taught to these students prior to chemical equilibria:

"… because we have explained ΔH is positive for endothermic, and ΔH is negative for exothermic reactions. And so, we can go back to that and say: "look, our endothermic reaction, you must heat it up to make it go, it's taking in energy. And so, if you're raising the temperature, you get more of that reaction happening". Going back to basic principles can help."

This is an example of how using basic concepts of energetics, can help students understand equilibria, such as how an equilibrium shifts in response to a change in conditions. This idea has also been noted by Cooper et al, who discussed the use of core ideas that can help students build a stronger framework for understanding chemical concepts, instead of discrete topics which are more likely to lead to misconceptions. (Cooper et al., 2017).

The Use of Demonstrations (30 %)

More/better practical demonstrations (15 %) has been shown to provide much needed support for students, who learn better from physical involvement, and then subsequently seeing how the concepts play out in real life (Basheer et al., 2016; Canpolat et al., 2006; Gabel, 2003; Piquette & Heikkinen, 2005). However, in the case of chemical equilibria, this can prove difficult due to this topic's theoretical nature. Their teacher explained an example regarding an $NO_2 \rightleftharpoons N_2O_4$ equilibrium between two gases, where N_2O_4 is a colourless gas and NO_2 is a brown gas, noting the experiment works well to display the effect of temperature change, and then doesn't extend to changes in pressure, limiting it in other aspects.

"We can shift into cold and hot water and see the colour change, as it goes between N_2O_4

and NO_2…the high pressure should shift it to the colourless gas, but because you're compressing it and particles get close together and actually you can't see the colour change"

There perhaps remains a demand for more effective and diverse experimental demonstrations for chemical equilibria, building on existing demonstrations, such as ion exchange in acid-base equilibria, colour change of copper (II) complexes, and experimental simulations.(Eilks and Gulacar, 2016; Rogers et al., 2000; Zingales, 2003)
The suggestion of more or better use of diagrams (8 %) and videos (7 %), both offer other suitable alternatives for students who have a preference for visual learning over taking notes, and this methodology for teaching chemical equilibria has been previously explored (Akaygun & Jones, 2014; Velázquez-Marcano et al., 2004)

Focus on Practice Questions and Worked Examples (15 %)
More practice questions (8 %) could be an effective means to identify misconceptions, and this has been noted in literature. (Banerjee, 1991; Hackling & Garnett, 1985; Johnstone et al., 1977; Maskill & Cachapuz, 1989). Their teacher agreed this to be an effective method, stating:

"I think that practice questions are a very good way for the students to test their knowledge and to identify points which they have not understood"

Since students are unable to know themselves if they have adopted a misconception, the marking of practice questions and feedback could perhaps be an effective method for "capturing" them, a method that is utilised in misconception research as a means of identifying areas of misconceptions (Banerjee, 1991; Hackling & Garnett, 1985; Johnstone et al., 1977; Maskill & Cachapuz, 1989)

Having worked examples (7 %) to questions on the other hand, could certainly benefit the students, giving them defined structures to use when tackling problems. However, a dependence on this method in terms of blindly following the examples, could in some cases reinforce student false understanding of concepts, whilst achieving good grades in this topic.(Bergquist & Heikkinen, 1990; Kurt & Ayas, 2012).

Other Suggestions
Other, less popular suggestions still provided an interesting insight into how students feel alternative teaching strategies could benefit their learning of chemical equilibria. An interesting set of suggestions, centred around making a "banned" list of common misconceptions (7 %), whereby the students could refer to a general list to know what to avoid, with one student suggesting:

"Making it clear what the misconceptions are and telling us what they are. Then giving us the correct answers"

Making students aware and dissatisfied with their misconceptions, is regularly mentioned in research as a step in conceptual change strategies (Özmen, 2007; Posner et al., 1982). Another set of suggestions around providing more case-study examples (5 %) could perhaps help students visualise the concepts in an application-based real-life example (such as the Haber process), utilised as reference points for the students to understanding difficult concepts, even if these examples are outside the formal syllabus (King et al., 2008; Kurt & Ayas, 2012; Modak, 2002; Russell et al., 1997).

In future work, these suggestions would be trailed for effectiveness by comparing to a control group, to measure whether consulting students' ideas is a successful approach to address their misconceptions.

Conclusions

Overall, this research has provided an insight into some common misconceptions that have been adopted by secondary school students when learning chemical equilibria, as well as offering possible suggestions for how these misconceptions could be addressed through teaching. To improve the accuracy and reliability of the data, a wider sample pool with more students and teachers from different schools and exam boards, would further support any following conclusions drawn.

Common misconceptions held by the students were found in a wide breadth of the areas of chemical equilibria: the characteristics of a dynamic equilibrium, the reactants and products of a dynamic equilibrium, and also the effect of conditions and catalyst on equilibrium. To expand on this, additional questions of a technical nature given to the students would possibly examine these misconceptions in more detail. Additionally, a 3–5-year longitudinal study following the same set of students could be useful in tracking the changes in misconceptions over time.

The key set of suggestions centred around ensuring a clear and comprehensive delivery of basic principles, use of practical demonstrations where applicable and finally supported the use of practice questions for the 'capture' of misconceptions. Trailing the success of the methods such as these is of considerable importance, to elucidate how practically viable they are in addressing misconceptions in chemical equilibria, and therefore the value of consulting students' ideas to address their misconceptions.

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