A CROSS-SECTIONAL STUDY OF SCIENTIFIC THINKING SKILLS OF LEARNERS AT VARIOUS LEVELS

Boo Hong Kwen
Nanyang Technological University, Singapore

Abstract: This paper reports on the results of a study which examined the ability of learners (N=100) at various levels (i.e., students at JC1 (junior college year 1) [N=25], JC2 (junior college year 2) (N=45), fourth year university [N=12] and post-graduate levels [N=23]) to think scientifically when presented with a range of familiar chemical phenomena. The main data collection instrument was the clinical interview. Each subject was interviewed in-depth for about one hour on a one-to-one basis. Each interview was taped, transcribed verbatim and then analysed. Five familiar chemical reactions were used as foci for discussion in the interviews. For each reaction, each interviewee was asked, among other things, to make predictions about the overall energy change involved, and to make explanations as to why the change took place, i.e., the driving force for the change. The results show that significant proportions of the interviewees across the various levels were using perceptually dominated thinking rather than conceptually dominated thinking; at the same time, they were unable to use science concepts consistently across the five reactions. It can thus be inferred that they were unable to think scientifically.

Introduction

According to Kuhn, Amsel and O'Loughlin (1988) the essence of scientific thinking is the skilful co-ordination of theory and evidence. Hawkins and Pea (1987) suggest that, among other things, to think scientifically is to be able to "offer explanations in terms of formal concepts that meet communal norms." Driver (1985) in the context of examining pupils' use of alternative conceptions discusses the notion of perceptually dominated thinking which is thinking based on observable features in a problem situation, in contrast to conceptually dominated or scientific thinking.

Thus, in this paper, in the context of discussing and explaining chemical phenomena, scientific thinking is taken to mean "conceptually dominated thinking" or "the ability to use currently accepted scientific concepts and models to make predictions and/or explanations consistently across a range of chemical phenomena". The use of perceptually dominated thinking is taken as a reflection of the lack of scientific thinking.

Purpose of Study

The purpose of the study was to examine the ability of students at various educational levels to think scientifically when presented with a range of chemical phenomena.

Sample of Study

The sample of 105 students was composed of 25 students at junior college year 1(JC1) level, 45 at JC2 level, 12 fourth year undergraduate chemistry students and 23 post-graduate students who were enrolled in a one year teacher education course.

Method of Study

The design of study detailed in Boo (1996, 1998) is based on study subjects' explanations of four key aspects of chemical reactions measured over five events, and the main data collection instrument was the clinical interview.

These five events involved were:

- hot copper in air;
- the burning candle;
- the bunsen flame;
- addition of magnesium to dilute hydrochloric acid; and
- addition of aqueous sodium chloride to aqueous lead nitrate.

The four aspects were:

- the type of change predicted;
- the overall energy change predicted;
- how the process of change is conceived or imagined; and
- the driving force for the change.

Each study subject was interviewed on a one to one basis. Each interview session, of about 1 hour duration, was audio-taped and subsequently transcribed. During each interview students were not only asked to verbalise their understandings of various aspects of the concept of chemical reaction but were also asked to make drawings to illustrate their explanations and theories.

Findings and Discussion

Since all the interview subjects had already been exposed to formal chemistry for some years, it is expected that they would have grasped the chemist's view of chemical reactions, outlined here:

> Chemical change involves the interaction between numerous particles which are in constant motion and which collide with one another, breaking existing bonds and making new bonds. Bond breaking requires energy and bond making evolves energy. The energy change in the reaction is a balance between these two processes. The reactions took place because there was a tendency towards thermodynamic stability: an increase in the entropy of the universe associated with the decrease in enthalpy of each system. In order to satisfy the kinetic conditions for the reaction to take place, sufficient activation energy must be provided.

In this section, two different kinds of evidence on the students' scientific thinking ability are discussed. One kind relates to instances where students' responses suggest the use of perceptually dominated thinking vis-à-vis conceptually dominated thinking. The other kind relates to students' inability to use science concepts consistently across the five events in predicting the overall energy change involved, i.e., aspect B.

Use of Perceptually Dominated Thinking

The results show that significant proportions of interviewees across the various levels were using perceptually rather than conceptually dominated thinking. For example, with respect to event 2 (the burning candle), the proportions of students at the various levels who used perceptually dominated thinking and hence stated that wax in a burning candle was not involved in any chemical reactions at all are shown in Table 1.

Table 1: Numbers and proportions of interviewees across the levels who thought wax in a burning candle was not involved in any chemical change at all

Educational level of subjects	Number involved in study	Number and proportion who thought wax not involved in any chemical change at all
JC1	25	19 (76%)
JC2	45	32 (71%)
Fourth year undergraduate	12	8 (66%)
Postgraduate	23	9 (39%)

The high proportions of students who did not think that wax in a burning candle is involved in any chemical reaction at all is a cause for concern, they suggest that years of education in science did not affect the way they view an everyday phenomena. To these students, only the candle wick was involved in burning; "*the wax was merely melting and re-solidifying*". Clearly these students were reasoning like the layman - since the wick and not the wax appeared to be alight or "*burning*" they inferred that the wax is not involved in any chemical change at all. To them the wax is merely melting, and is thus undergoing only a physical change. These students appeared to be using what Driver (1985) described as "*perceptually dominated thinking*" rather than "*conceptually dominated thinking*" and were similar to those students reported by Abraham, Williamson and Westbrook (1994), BouJaode (1991), Hesse and Anderson (1992) and Ribeiro, Costa Pereira, and Maskill (1990).

As expected, the proportions shown in the last column of Table 1 show a decreasing trend, in line with the increase in educational level as well as physical age of the students.

Inability to apply scientific concepts consistently across events

With respect to the overall energy change involved (aspect B), it was expected that interview subjects across all levels should have little difficulty in predicting that all five reactions discussed are overall exothermic reactions (the first four being well-known redox reactions, while the overall exothermic nature of the lead nitrate-sodium chloride reaction could have been inferred by considering the decreased in entropy of the system). It was also expected that they should be able to go on to suggest that there was net heat evolved because "*the bonds that were being made were stronger than the bonds which were being broken*."

Instead, only a small proportion of the interview subjects at each level predicted correctly that all five reactions discussed are overall exothermic and at the same time were able to use the accepted science concept that in all five reactions, "*the bonds that were being made are stronger than the bonds that were being broken*."

The rest offered a range of different reasons why a particular reaction is exothermic or endothermic. Overall, as shown in Table 2, very significant proportions of interview subjects at each level were not able to use the relevant science concepts consistently in discussing the energy change involved across the five reactions.

Table 2: Numbers and proportions of students who did not use appropriate science concept in discussing energy change across the five events

Educational level of subjects	Total number involved in study	Number and proportion who did not use appropriate science concept in discussing energy change across five events
JC1	25	22 (88%)
JC2	45	39 (87%)
Fourth year undergraduate	12	10 (83%)
Postgraduate	23	19 (83%)

These students appeared not to have fully grasped the conceptual meaning of scientific terms involved which means that they were unable to appreciate the full significance and predictive power of these scientific concepts. The following responses of three students JC_9 (a second year junior college student), U_4 (a fourth year undergraduate student) and G_{10} (a post-graduate student) on aspect B are presented in the following Tables 3, 4 and 5 as illustrations. In as far as any student can typify other students, these were typical students in that they each used a variety of different ideas to account for the overall energy change involved.

Table 3: Responses on aspect B (overall energy change predicted) across five events of a typical student in the junior college group, JC9

Event	Energy change	Reasons
1	Endothermic	Because without heat being taken in, there is no reaction
2	Exothermic	Because you can feel the heat with your palm.. heat comes from burning of wax.. wax is a fuel.. it stores chemical energy.. this energy is released when wax burns.
3	Exothermic	Because number of bonds broken on reactant side are greater than number of bonds formed on product side.. bond breaking releases energy.. bond making needs energy.
4	Exothermic	Because of strong ionic bonds formed between magnesium and chlorine.. less energy is absorbed in breaking the H-Cl bond than is released in bond making.
5	Endothermic	Because all precipitation reactions are endothermic.. I don't know why but I remember reading somewhere..

Table 4: Responses on aspect B (overall energy change predicted) across five events of a typical student in the undergraduate group, U4

Event	Energy change	Reasons
1	Exothermic	Because oxidation reaction is always exothermic.. here you have copper foil undergoing oxidation, hence I think the reaction will release energy.. oxidation is always exothermic
2	Exothermic	Because wax is a fuel, it stores energy and when it burns, it releases the energy stored in it…
3	Exothermic	When you light the bunsen flame, the spark excite the electrons in methane.. and in oxygen in air.. they go to a higher energy level.. Then they share their orbitals.. they form bonds.. the electrons go down to a lower energy level.. they give up excess energy.. in the form of the light you see and the heat of the bunsen flame
4	Exothermic	I remember doing the experiment. It is definitely exothermic. The test-tube felt very warm.. hot..(Upon persistently probed by the interviewer to give a reason, the student finally suggested the following reason) I think the H-H bond formed is stronger than the metallic bonds in magnesium which are being broken.. that is why it is an exothermic reaction..I am assuming that the bonds involved in solvation step can be neglected of course...
5	Endothermic	I remember doing the experiment.. you can feel the test tube, it is cold.. (Upon persistently probed by the interviewer to give a reason, the student finally suggested the following reason) Why is it endothermic? Because a bond is formed. You need energy to form a bond. Energy is absorbed from the environment to form the bond so the test tube feels cold.

Table 5: Responses on aspect B (overall energy change predicted) across five events of a student typical of the post-graduate group, G10

Event	Energy change	Reasons
1	Exothermic	Formation of copper oxide releases energy.. Energy from the heat.. breaks the metallic bonding in copper.. also break the covalent bond in oxygen.. Then for formation of copper oxide bond, forming of a bond.. will release energy. So.. with this release of energy.. I presume it'll be an exothermic reaction.
2	Exothermic	Wax is a fuel.. it stores chemical energy.. this energy is released when wax is burned.
3	Exothermic	When you burn methane.. you're supplying energy to break the bonds between C and H, and oxygen.. Then they'll form CO2 and H2O. Being more stable because they've lower energy states than the reactants.. these products are more stable because of the strength of their bonding and the number of bonds too.
4	Exothermic	The bonding between.. magnesium and the chloride is stronger than.. the bonding in magnesium and in dilute HCl.
5	Endothermic	(Subject took a long time to provide reasons.) Formation of a solid.. somehow the product is at a higher energy state.

The results thus show that the majority of the interview subjects appeared unable to think scientifically. Reasons for the lack of scientific thinking ability were explored in post-interview discussions with interviewees across all levels.

The outcome reveals that students inability to think scientifically could be broadly classified into three inter-related categories, viz., those that relate to (1) the learner; (2) the instructor/teacher and, (3) the curriculum.

Reasons associated with the learner

With respect to the learner, many reasons could be offered. One reason could be the tendency of students to reduce theoretical knowledge and principles to factual level and to apply this in a rote manner. In a situation where learners view the syllabus content as loaded, this rote learning could be more prevalent (see curriculum-related reasons). In addition, rote learning might be further encouraged if the learner views science as predominantly a collection of facts.

Yet another reason relates to preconceptions or pre-existing misconceptions that learners might have with respect to certain concepts which would hence impede the acquisition and use of scientific concepts in their thinking.

Reasons associated the instructor/teacher

There are research studies as well as anecdotal evidence which show that the instructors/teachers themselves could be lacking in scientific thinking ability or could be harbouring misconceptions about science concepts; and these could contribute to the learner's acquisition of misconceptions and lack of scientific thinking ability.

Another reason relates to the pedagogical method. If the instructor/teacher fails to help learners appreciate the aim of science as the establishment of generalisations about the behaviour of the natural world (Chalmers, 1990) and the nature of science as both a product and a process of construction of predictive conceptual models (Gilbert, 1991) and instead presents science as nothing more than a collection of facts, rules, algorithms and procedures to be memorised, then it would not be surprising if the learner tends to apply these by rote and hence cannot think scientifically.

Reasons associated with the curriculum

Among the reasons related to curriculum is the loaded syllabus or loaded time table. This could then mean that there might not be adequate opportunities to allow students to internalise concepts gradually, which could result in poor long-term memory retention. In order to handle high information volume some students tend to adopt surface learning strategies, i.e., rote memorisation rather than seeking meaningful linkages. Another reason relates to the inadequate description of the nature of science in the curricular materials; also the presentation of the content in the form of independent, disjointed topics, which tends to encourage students to compartmentalise topics in a way which hinders the understanding of generic concepts, principles and models across topics.

No single factor operates alone. Instead, a variety of these factors operate in concert to result in students' lack of scientific thinking ability. Clearly further research is necessary to examine how scientific thinking can be fostered across all levels.

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