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A study of students’ understanding of the nature of science and their higher-order thinking skills in biology

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Abstract: The purpose of this study was to elucidate the relationship between students’ understanding of the nature of science (NOS) and their ability to answer higher-order thinking (HOT) questions in biology. A class of 37 secondary 3 students completed a survey to assess their knowledge of the NOS. The students also took an achievement test containing HOT questions based on topics (diffusion, osmosis, enzymes) that they had studied. Next, enrichment lessons on NOS were introduced for four weeks, after which the NOS survey and a parallel achievement test were administered again. The mean score of the post-enrichment survey was significantly higher than that of the pre-enrichment survey showing an improvement in the students’ understanding of NOS although some misconceptions persisted. The mean scores on the achievement tests before and after the enrichment programme did not reflect any significant difference. There was no significant correlation between the pre-enrichment NOS survey and HOT achievement scores but a small positive correlation was observed between the post-enrichment scores. This suggests that students who had a better understanding of NOS performed better on the HOT achievement test, despite no difference observed between the pre- and post-enrichment achievement scores. The implications of these findings will be discussed.

INTRODUCTION

In this era of the knowledge-based economy, students have to be equipped with the skills to construct knowledge through engaging in complex mental operations that involve scientific concepts and higher-order cognitive operations (Zohar, 2004). Also, students who engage in complex mental operations involving the nature of science (NOS) will not only have a clear understanding of the NOS but also be equipped with the ability to understand scientific concepts at a deeper level. They will be able to learn scientific concepts, principles and models meaningfully to use them in explaining or making predictions of a wide range of unfamiliar phenomena.

In view of this, reforms in science education in the United States and elsewhere have placed extensive emphasis on scientific inquiry and NOS as cognitive outcomes (e.g., Abd-El-Khalick et al., 1998, 2000; Lederman et al, 1992, 1998, 2002). The inquiry approach is advocated because it helps students to gain an understanding of the process of construction and synthesis of scientific knowledge. An understanding of the NOS (Abd-El-Khalick, Bell & Lederman, 1998) would help students to understand that scientific knowledge is durable yet tentative. Students who understand this would be less cynical of the scientific enterprise and be less confused by the changing of science concepts learnt in the face of new evidence. They will be less likely to perceive science as a body of literal truths and understand that the
notion of tentativeness in the NOS is a strength rather than a weakness (Driver et al., 1996; McComas et al., 1998).

Previous research in the 1960’s indicated that there was no correlation between students’ understanding of NOS concepts and their science content knowledge (Craven, 1966; Olsted, 1969). However, a later finding by Songer & Linn (1991) showed that students who possessed a knowledge of the NOS were better able to construct a dynamic view of science and develop a better conceptual understanding of complex topics like thermodynamics. The authors reported that the students who viewed science as being dynamic rather than static, understood that scientific knowledge is tentative and concluded that the best way to understand complex knowledge was to understand how the scientific ideas were related. Thus, the aim of teaching students the NOS is to help them become aware of the processes involved in the development of scientific knowledge.

To convince educators that an understanding of the NOS would enhance the learning of science content in students and help them evaluate the strengths and limitations of the different types of scientific knowledge (McComas et al., 1998), more studies need to be done to determine whether understanding the NOS supports successful learning of science content. The purpose of this study, then, was to elucidate the relationship between students’ understanding of the nature of science (NOS) and their ability to answer higher-order thinking questions in biology. The questions that this study aimed to address were:

1. Is there any difference between students’ views on the nature of science (NOS) before and after their participation in an enrichment programme on the NOS?
2. What is the relationship between students’ understanding of the nature of science and their ability to answer higher-order thinking questions?

Students’ ability to answer higher-order thinking questions was used as an indicator of the quality of their learning.

**METHOD**

A class of 37 secondary 3 first students completed a pre-enrichment survey adapted from Lederman’s View of Nature of Science Form C (VNOS) (Lederman et al., 2002) to assess their knowledge of the NOS. The NOS survey was an open-ended instrument which focused on seven concepts of NOS which students subsequently encountered in the enrichment lessons. The rationale for not using a forced-choice instrument was that the respondents might not understand a certain statement in the same way that instrument developer would, thereby threatening the validity of the study (Aikenhead, Ryan, and Desautels, 1989 in Abd-El-Khalick and Lederman, 2000). Forced-choice instruments may reflect the instrument developer’s biases and views of NOS and impose bias in the respondents taking the tests. The data collected was validated by informal interviews to clarify doubts about what the student had written. A rubric of the NOS aspects was used to quantify the survey results for further analysis. In the rubrics, a score of “2” indicated that students’ views were normative, according to the descriptions given in Lederman et al. (2002); “1” indicated a partially accurate view; and “0” indicated no relevance at all.

The students also took an achievement test containing higher-order thinking skills (HOTS) questions based on topics (diffusion, osmosis, enzymes) that they had studied. The HOTS questions were achievement test questions obtained from past-years exam papers and they
comprised both multiple-choice questions and open-ended, structured questions. In each of the HOTS test, there were three multiple-choice questions and two open-ended, structured questions. The maximum marks for the pre- and post-enrichment HOTS tests were 18 and 14 respectively. Both tests were scored according to the number of correct responses the students provided. The level of cognition required to answer the questions were based on Bloom’s taxonomy of application, analysis and synthesis levels.

Next, enrichment lessons on NOS were introduced for four weeks, after which the NOS survey and a parallel achievement test were administered again. There were four 1.5-hour lessons conducted over a period of 4 weeks. In each of the enrichment lessons, students were introduced to the concept of NOS through a series of inquiry activities and discussions on the topic of evolution. The activities were structured to simulate the process of how scientists carry out inquiry, interpret evidences and develop theories. The inquiry activities such as the “Great Fossil Find” and “The Footprints” used were developed by the National Academy of Sciences (1998).

In the “Great Fossil Find” students took part in a role play to simulate how scientists work in the field of paleontology. Fossils collected were matched to a given list of bone structures of existing organisms, for example a bird, a bat, a fish, a salamander, a cat, a rabbit and a frog. As pieces of the fossils were gradually found, students changed their mental framework of what the organism was and attempted to predict how these animals lived, what they ate and how they hunted or scavenged for food. This activity attempted to introduce to the students that science is durable but tentative. There is no single scientific method. Data from observation studies and comparative studies are valid, and a scientist’s theoretical framework and beliefs can influence his or her work. In the “Footprints”, students were shown a picture of two sets of intertwined footprints and asked to predict what happened. The objective was to help students differentiate between observation and inferences and to impress upon the students that scientific knowledge is empirically-based and theory-laden.

After the enrichment lessons, the post-enrichment NOS survey and a parallel achievement test were administered. The qualitative and quantitative data were tabulated and analyzed. The scores of both the pre- and post-enrichment achievement test and surveys were analyzed using paired t-test. These results would show if the enrichment programme had been effective in making students more aware of the NOS aspects. A correlation analysis between the pre-enrichment survey and HOTS test and the post-enrichment survey and HOTS test would provide insight into the relationship between students’ understanding of NOS and ability to answer HOTS questions.

RESULTS

Students’ pre- and post-enrichment understanding of the nature of science

There was an increase in the students’ understanding of NOS after the enrichment programme. The post-enrichment mean score (M = 6.3) was significantly higher than the pre-enrichment mean score (M = 5.5), t = 2.2, df=36, p<.05 , indicating that most students had a naïve view of NOS prior to the enrichment lessons and a slightly more informed view after the enrichment lessons.

There was a weak but positive correlation between the pre-enrichment survey scores and post-enrichment survey scores (r = .346, p< .05). This indicated that students who possessed a
more informed view of NOS and scored well in the pre-enrichment survey also did correspondingly better for the post-enrichment survey.

Table 1 shows illustrative comments from students about their understanding of the NOS before and after the enrichment lessons. In the class of 37 students, many responses were collected, including some misconceptions that the students held about the NOS. The selected responses in Table 1 show examples of both students’ naive and more informed views of NOS before and after the enrichment lessons. Compare, for example, the pre- and post-enrichment responses of students 24 and 25 where their understanding of the NOS showed some improvement after the enrichment lessons. For theme 4 on the tentativeness of NOS, another student (student 35) wrote, “theory can change...when a new and more convincing theory comes up and it makes more sense....” during the pre-enrichment survey. Her response indicated that she was aware that scientific knowledge is tentative but she did not cite an example. However, in the post-enrichment survey, she included a more specific example on the heliocentric versus the geocentric view of the solar system.

Some students still retained their naive conceptions of the NOS in the pre-enrichment survey. For example, student 12 wrote, “Science is very objective and does not require people to state their opinions on any matter. In contrast, other disciplines of inquiry requires people to think for themselves and there can be different points of views....”. Despite an improvement in her response on the post-enrichment survey, she still showed an incomplete grasp of the subjective nature of theory-laden NOS in that she thought that “Although both science and religion is subjective, science is to some extent very factual and not controversial, especially physics...”.

Students’ pre- and post-enrichment higher-order thinking skills
The students’ HOTS test scores before (M = 55.1) and after (M = 56.0) the enrichment programme did not reflect any significant difference (t = .284, df =36, p>.05). This indicated that students did not perform differently in their ability to answer HOTS questions after undergoing the NOS enrichment module. There was no increase in their ability to analyze and apply their knowledge to higher-order thinking questions.

The relationship between the students’ understanding of the nature of science and their higher-order thinking skills pre- and post-enrichment
There was no significant correlation between the pre-enrichment VNOS and HOT achievement scores but a small positive correlation (r=.375, p<.05) was observed between the post-enrichment VNOS and HOTS scores. This suggests that after the enrichment module, students who had a better understanding of NOS performed better on the HOT achievement test, despite no difference observed between the pre- and post-enrichment achievement scores.
Table 1: Illustrative examples of students’ views of the nature of science (NOS)

<table>
<thead>
<tr>
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<td>1. Empirical NOS</td>
<td>How is science different from religion or philosophy? (Student 12)</td>
<td>Science is the study of the things around us. Science is very objective and does not require people to state their opinions on any matter. In contrast, other disciplines of inquiry requires people to think for themselves and there can be different points of views depending on different people.</td>
<td>Science is the study of the things around us and the explanation of why certain things happen. Science requires real evidence such as the fossils of dinosaurs to prove a point. Although both science and religion is subjective, science is to some extent very factual and not controversial, especially physics. They are also different because science can have modifications over a long period of time as more discoveries are made, while other disciplines of inquiry are usually standard and never change.</td>
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| 2. The scientific method | What constitutes an experiment? (Student 25) | Apparatus are needed. | Experiment is the procedure of discovering new things. Steps taken:  
- State the objectives and aims  
- Think of a hypotheses to the experiment  
- Observe and record the observations down for further studies |
<p>| 3. Validity of observationally based theories and disciplines | Are experiments needed to validate the development of scientific knowledge? (Student 24) | Yes. New theories can be made known after discovering observed (observations) and proven through experiments. | No. Some are based on inference and observations. For example, we get the information on dinosaurs through paleontologists who also derive their knowledge by inferring through the fossils and evidence they find. |</p>
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<td>4. Tentative NOS</td>
<td>Are scientific theories tentative? (Student 35)</td>
<td>Yes, the theory can change. They change when a new and more convincing theory comes up and it makes more sense. <em>We bother to learn scientific theories so</em> that we can try to understand things around the world that we can never really experience (e.g. evolution theory, dinosaurs, astronomy)</td>
<td>The theory might change. When other scientists find out something that seems more fitting to the subject, the new theory would be inculcated into the old theory and thus a new and improved theory would be formed. E.g. when people thought <em>that the Earth</em> was the centre of the solar system. Now we know it is the sun. <em>We bother to learn scientific theories as</em> it helps us understand the world better and gives us a basis for guessing about further things in the universe.</td>
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<td>5. Theory-laden NOS</td>
<td>Are conclusions drawn by scientists theory-laden? (Student 25)</td>
<td>Some fossil bones were burnt by meteorite and some were burnt by the larvae (<em>lava</em>) from volcanic eruptions.</td>
<td>They may have used the same set of data to deliver their conclusion but because they have different perspectives as to how things happen, therefore they came up with different conclusions. These different conclusions are possible because both have their own reasons and no one can actually justify which one is the accurate one. Therefore before the ultimate conclusion is formed, all explanations are possible.</td>
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<td>6. Social and Cultural embeddedness of science</td>
<td>Are scientific theories influenced by social &amp; cultural values?</td>
<td>Not sure.</td>
<td>I believe that it does reflect social and cultural values. The values instilled in these people would affect the way these people think, and if they come up with theories, it would thus reflect their own social and cultural values.</td>
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Table 1 (continued): Illustrative examples of students’ views of the nature of science (NOS)

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<td>7. Creative and imaginative NOS</td>
<td>At what stage of the investigation is creativity required in science? (Student 16)</td>
<td>Yes, they do. In order to first come up with an experiment you must first use your imagination to think of the experiment. In the planning and design process, creativity is needed to think of how to carry out the experiments. Only with a bit of imagination and creative juices, is an experiment/ investigation able to be done. For instance, to come up with certain theories, scientists use their imagination to come up with possibly a certain circumstance to happen.</td>
<td>Yes. Scientists do need to have creativity and imagination for experiments and investigations. In planning and design, scientists have to be creative and imaginative of what their experiments should be like and how it should be done. After data collection, they have to come up with an explanation for their conclusions of the test. Scientist also use creativity and imagination (with evidence though, of course) to think of theories of why and how things happen. For example, of how dinosaurs became extinct, imagination and creativity made two different answers from the same set of data to be possible.</td>
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DISCUSSION AND CONCLUSION

The higher mean score in the post-enrichment NOS survey relative to the pre-enrichment NOS survey showed that students had a more informed view of the NOS after the enrichment. Even though there was a general improvement in the students’ NOS concepts after the enrichment programme, a closer analysis of the survey results showed misconceptions pertaining to some of their views. A possible reason could be that although these students had understood some concepts of NOS, they had not fully integrated that knowledge into intuitive beliefs and ultimately into principles, thus leading to misconceptions in NOS (Songer & Linn, 1991).

The results obtained in the t-test for the HOTS tests did not demonstrate a similar trend as found in Songer & Linn’s (1991) study. In the present study, the increase in NOS knowledge did not reflect any difference between in the students’ HOTS scores before and after the enrichment programme. One possible reason could be that the tests focused more on science content knowledge and not on science knowledge construction. Although the HOTS
questions required students to apply scientific concepts and to analyze data presented, the situations were somewhat familiar to the students and the questions did not require them to apply NOS concepts to construct new scientific knowledge in unfamiliar settings. Generally, the HOTS tests yielded results that were consistent with the earlier findings by Craven (1966) and Olsted (1969) that there was no relationship between understanding NOS and in the mastery of science content. For future studies, a HOTS test should be crafted to incorporate testing of the elements of NOS, as well as using students’ newly acquired knowledge of NOS to construct predictions of unfamiliar situations. It would also be interesting to find out whether using NOS and the inquiry approach to build scientific knowledge in science curriculum would make a difference in the student’s ability to answer HOTS questions of less familiar situations.

The lack of correlation between the pre-enrichment VNOS and HOTS scores was expected as students possessed naïve understanding of NOS and they also had variable abilities in answering HOTS questions. The small positive correlation between the post-enrichment VNOS and HOTS scores indicated that students who were weak in grasping complex concepts of NOS also had more difficulty in answering the HOTS questions. In contrast, those that had better VNOS scores would also be more likely to do better on the HOTS questions. This implies that a better understanding of the nature of science is associated with the use of higher-order thinking skills.

One limitation of this exploratory study is that there was no control group. Due to the restrictions of class schedules and the banding of students into different classes based on their academic abilities, it was not possible to achieve the ideal design in this investigation. It would be more ideal to engage another class of comparable ability as a control group to enhance the design of the study or to randomize the students in the two groups. Further studies in this area could focus on students’ understanding of NOS and their ability to construct scientific knowledge through a higher-order thinking test that would require them to integrate their knowledge of NOS to make predictions of unfamiliar outcomes.

REFERENCES


