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In-service Science Teachers' Dimensions of Knowledge in the Physical Properties of Gases using Concept Maps

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ABSTRACT

In-service science teachers' dimensions of prior knowledge about the physical properties of gases were studied using concept maps. Thirty science teachers, who were enrolled to a summer in-service undergraduate program in a university in Ethiopia, were guided to draw concept maps of the macroscopic and microscopic properties of gases. Qualitative framework thematic analysis method was used to analyse the concept maps. The analysis method utilized the 'revised taxonomy for structure of the knowledge dimension' to classify the themes. The results revealed three dimensions of knowledge with their related percentage extensiveness - factual (43%), hierarchical conceptual (16%) and relational conceptual (22%). The results also showed a dimension of misconceptions (19%) about the physical properties of gases. It was shown that the in-service science teachers' knowledge of gases was predominantly factual rather than conceptual, and that they also held misconceptions which needed to be corrected. The concept maps were found to be valuable in identifying the factual and conceptual knowledge as well as misconceptions. It is recommended that science teachers should develop their conceptual knowledge and minimize their misconceptions not to confuse students during their teaching in school. This method of identifying learners' dimensions of knowledge can be applied to any knowledge content area in science education to facilitate and support learning.

Keywords: concept maps, knowledge dimension, prior knowledge, misconception, science teachers

INTRODUCTION

Many of the concepts studied in science are abstract and inexplicable without the use of scaffolding of physical and mental models. Gases as a topic is the focus content in this research because they rest upon an understanding of the properties and behaviour of matter in science education. In science, gases are observed and can be studied at the macroscopic and microscopic levels. The complexity of the concepts of gases poses many difficulties in understanding basic science concepts for school and university students especially learners coming from poor resourced high schools (Bain & Towns, 2016; Ramnarain & Joseph, 2012). The difficulties experienced in learning science and in particular gases are magnified as its concepts are consolidated through the use of mathematical symbols, formulas and equations. Mathematical equations of gases are used express and connect relationships at the macroscopic and microscopic levels (Robertson & Shaffer, 2013). The use of chemical symbols, chemical formulas, and chemical equations also add additional complication to the learning of gases. The problem is that in-service science education teachers also need to know the dimensions of their science knowledge and rectify their misconceptions in science to strengthen their subject matter knowledge and to recognize the errors that their own students might make.

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Educators who employ constructivists' principles in teaching seek the prior knowledge of their students in order to build new knowledge (Cakir, 2008). Traditional approaches typically use questioning and recalling of previous understanding to assess their students' understanding. A more directed and useful demonstration of pre-constructed knowledge is the use of hand-drawn concept maps. Concept maps, often referred to mind-maps or a network of spider diagrams, are helpful for constructing and understanding information (Cañas & Novak, 2010; Novak & Gowin, 1984).

Cognitive knowledge structures in content knowledge areas such as science and in particular physics are usually formed hierarchically with networks of concepts linked to other concepts, laws and principles which are fundamentally interdependent (Koponen & Nousiainen, 2013; Novak, 2002). The organization of teachers' knowledge in hierarchically rich content areas of science has a direct impact on their teaching and the way in which their students learn in or out of classroom. Concept maps have been found to be a better means to reveal cognitive knowledge structure than paper-and-pencil questionnaires. They also need to explore new and innovative instructional strategies that can help their students to collaborate together and create organized knowledge structures to improve their learning (Lăcrămioara, 2015).

It is expected that science teachers will have detailed understanding of content knowledge and pedagogical content knowledge prior to mentoring their students to construct in-depth scientific knowledge. However, there is a lack of studies investigating how in-service science teachers understanding of gases develop while using concept maps and their classification of knowledge in terms of "the structure of the knowledge dimension of the revised taxonomy" (Krathwohl, 2002). This lack of studies on in-service science teachers' dimension of cognitive knowledge is observed in the context of poor resourced developed countries. This research explored how in-service science teachers understand the physical properties of gases for high school teaching by using concept maps drawn. This study will support educators' use of the concept maps, and help them categorize their knowledge structure and identify misconceptions of their students. The findings will assist the science teachers in designing appropriate constructivist approaches and to meaningful learning in the area of science. The research questions addressed are:

1. What kinds of cognitive knowledge dimensions of the properties of gases can be identified from the in-service science teachers drawn concept maps?
2. How are the revealed cognitive knowledge dimensions of the in-service science teachers distributed through their concept maps?

Cognitive Knowledge and Misconceptions in Gases

Science students fail to properly interpret or apply the gas laws after instruction in introductory physics and chemistry courses (Kautz et al., 2005a). They also confuse concepts of heat, temperature, and internal energy. Studies have shown that even after having been taught the properties of gases, such as weight and volume, the majority of high-school students and in-service teachers still believe that a gas has no weight and these misconception or intuitive conceptions often arise from their daily life experiences, which are in conflict with the correct scientific conceptions (Lin et al., 2000). These misconceptions of gases impede the in-service teachers' and their students' construction of knowledge regarding the properties of gases.

In order to have a detailed cognitive knowledge of gas laws, learners at different ages of schooling as well as at tertiary level need to understand the properties of gases at various levels: at the macroscopic level, which includes observable phenomena and processes (Kautz et al., 2005a); at the microscopic level, which relates the arrangement and motion of particles (Kautz et al., 2005b); and at the symbolic level, which is the mathematics and chemical notations of a situation (Roehrig & Garrow, 2007). In the symbolic understanding of gases, students have difficulties in completing problem solving process. In some cases, this is due to their failure to convert units for temperature, pressure or volume and numbers into scientific notation correctly as required by the formulae (Schuttlefield et al., 2012). In addition to the prevalence of misconceptions on the macroscopic and microscopic levels, students do not understand the meaning of the symbols used to represent the macroscopic and microscopic levels (Kibar et al., 2013; Robertson & Shaffer, 2013). Many of the misconceptions of high-school students also apply to final year pre-service and in-service teachers and this is of serious pedagogic concern.

Revised Taxonomy for Structure of Knowledge Dimensions

This research focuses on the study of in-service teachers' cognitive knowledge structure of the physical properties of gases, which can be revealed through analysis of their concept maps. The relevant education

Table 1. Structure of the knowledge dimension of the revised taxonomy

1. *Factual Knowledge*– The basic elements that students must know to be acquainted with a discipline *a.* Knowledge of terminology *b.* Knowledge of specific details and elements
2. *Conceptual Knowledge*– The interrelationships among the basic elements within a larger structure that enable them to function together a. Knowledge of classifications and categories b. Knowledge of principles and generalizations c. Knowledge of theories, models, and structures
3. *Procedural Knowledge* – How to do something; methods of inquiry, and criteria for using skills, algorithms, techniques, and methods a. Knowledge of subject-specific skills and algorithms b. Knowledge of subject-specific techniques and methods c. Knowledge of criteria for determining when to use appropriate procedures
4. *Meta-cognitive Knowledge* – Knowledge of cognition in general as well as awareness and knowledge of one's own cognition a. Strategic knowledge b. Knowledge about cognitive tasks, including appropriate contextual and conditional knowledge c. Self-knowledge

Source: Krathwohl, 2002

taxonomy of classifying educational objectives, namely, the 'structure of the knowledge dimension of the revised taxonomy' (Krathwohl, 2002) was examined and utilized as a framework for the purpose of classifying and identifying in-service science teachers understanding of the properties of gases (see **Table 1**).

The knowledge structure included in such taxonomies is applicable to fundamental topics in education. This study was delimited and restricted to the first two cognitive structure levels in **Table 1**, and excluded the procedural and meta-cognitive knowledge aspects as concept map data itself encompasses these two levels. It was more appropriate to initially focus on the factual and conceptual cognitive aspects of science concepts because procedural and meta-cognitive aspects come after establishing the basic knowledge structure. The factual and conceptual knowledge structures specify the 'what' of a particular concept which is the research question in this study, while the procedural and meta-cognitive knowledge structures establish the 'how' of accomplishing the task related to that concept (Teodorescu et al., 2013).

MATERIALS AND METHODS

The purpose of this study was to categorize and represent in-service science teachers' dimensions of cognitive knowledge structure acquired from high school and undergraduate introductory physics & chemistry education textbooks, namely gases, using concept mapping. It was assumed that each in-service science teacher's knowledge of gases would be different and that the common research tools such as survey tests would be inadequate to make sense of such intricate structures. The study involved 30 in-service diploma holder science teachers enrolled to study physics education in the summer degree program at a university in Ethiopia.

At the start of the Physics Subject Area Method II course, the in-service science teachers were trained for two hours on how to draw and use concept maps before the collection of data. They spent one hour in drawing sample concept maps using examples and templates as suggested by Vanides et al. (2005). In the follow up session of one hour, data were collected from the in-service teachers using concept maps (Cañas &Novak, 2010). Once the data were collected the in-service teachers' concept maps were transcribed, coded and categorized into themes based on the thematic analysis method (Ritchie & Spencer 2002).

Data collected from the 30 participants' concept maps were analysed using framework thematic analysis (Ritchie & Spencer 2002). During the analysis, "the revised taxonomy of structure of the knowledge dimension" (Krathwohl, 2002) was used to categorise the factual and conceptual knowledge structure of gases. The extensiveness of the emergent categories of the in-service teachers' conceptions in each category was analysed by grouping similar conceptions into a common category. The number of items in each category was counted to provide a frequency count. The extensiveness in each category is represented by the total frequency of the in-service science teachers' conceptions. This extensiveness mainly helped to show the disparities of concentration of the in-service teachers' conceptions in the categories.

RESULTS

The first research question seeks to answer to the kinds of cognitive knowledge dimensions of the physical properties of gases from the in-service science teachers' concept maps. The analysis of the 30 concept maps revealed four themes of the in-service teachers' understanding of the physical properties of gases. Among these, three were dimensions of cognitive knowledge structure and one was a dimension of misconceptions (**Tables 2-6**). The three dimensions of cognitive knowledge structure were factual knowledge, hierarchical conceptual knowledge and relational conceptual knowledge. Misconception was also a theme emerged as an alternative conception of the in-service science teachers. In terms of Krathwohl's (2002) taxonomy (**Table 1**), this framework knowledge structure of the in-service science teachers understanding of gases encompasses one category of declarative knowledge (factual), two categories of conceptual knowledge (hierarchical and relational) and a category of misconceptions.

Factual Knowledge

As shown in **Table 2**, thirteen factual knowledge items with extensiveness of 141 (43%) were depicted from the 30 concept maps data. This dimension of cognitive knowledge was the threshold cognitive understanding needed in the learning of gases. Factual knowledge, for example, the dependence of volume and shape of a gas on its container, and molecules in random motion as constituents of a gas, were most frequently depicted, involving more than two-third of the participants.

Table 2. Frequency and extensiveness of factual knowledge

Factual knowledge	frequency
1. Gases take the volume and shape of the container	20
2. Gases have molecules in random motion	18
3. Real gases have intermolecular forces	17
4. Ideal gases have negligible intermolecular forces	16
5. Temperature is due to successive collisions of gas particles	12
6. Real gases behave as ideal gas at high pressure and low temperature	11
7. Real gases are deviated from ideal gases	8
8. Real gases consist of molecules which move at different speeds	8
9. Gases have lower densities as compared to solids and liquids	7
10. Real gases have variable heat capacity	7
11. Ideal gases have identical particles of zero volume	7
12. Pressure measures the collisions of gas particles	6
13. Motion of particles results kinetic energy	4
Extensiveness	141

Hierarchical Conceptual Knowledge

Four hierarchical conceptual knowledge items with extensiveness of 52(16%) were analysed from the in-service teachers concept maps (**Table 3**). Most of the in-service teachers hierarchically drew the three gas laws under an overarching 'gas laws' heading.

Table 3. Frequency and extensiveness of hierarchical conceptual knowledge

Hierarchical conceptual knowledge	frequency
1. Ideal gases obey Boyle, Charles and Gay-Lussac's law	19
2. Gas is a phase of matter	13
3. Ideal gases have properties, like pressure, temperature and volume	12
4. Gases are atoms or molecules	8
Extensiveness	52

Relational Conceptual Knowledge

Relational conceptual knowledge describes the in-service teachers' knowledge of the relationships between two or three characteristic variables of gases namely, volume, pressure and temperature. More than three-

Table 4. Frequency and extensiveness of relational conceptual knowledge

Relational conceptual knowledge	frequency
1. General Gas Law combines the three gas laws as $P_1V_1/T_1=P_2V_2/T_2$	15
2. Boyle's Law states that pressure is inversely proportional to volume, i.e., $P_1V_1=P_2V_2$	13
3. Gay-Lussac's Law relates pressure and temperature, i.e., $P_1/T_1=P_2/T_2$	12
4. Charles' Law relates volume and temperature as $V_1/T_1=V_2/T_2$	12
5. The Ideal Gas equation is given as PV=nRT	10
6. Temperature is direct proportional to molecular kinetic energy	8
7. Kinetic energy is given in terms of mass and speed of the molecules	5
Extensiveness	75

Table 5. Frequency and extensiveness of misconceptions

Misconceptions	frequency
1. Gases are divided into real and ideal gases	18
2. Atmospheric pressure is denser at earth's surface due to earth's gravity	8
3. Real gases have volume, but ideal gas have no volume	6
4. Kinetic theory explains only ideal gas behaviour	5
5. Molecules in gases undergo only elastic collision	5
6. Pressure is dealt with in the ideal gas equation	5
7. Real gases have no attraction or repulsion force between the molecules	5
8. A real gas has density due to rising pressure	4
9. Volume of a gas is low	3
10. High pressure results in collisions between molecules	3
Extensiveness	62

Table 6. Knowledge structure and percentage extensiveness

Prior knowledge dimension	extensiveness
Factual	141 (43%)
Hierarchical	52 (16%)
Relational	75 (22%)
Misconception	62 (19%)
Total	330 (100%)

fourth of the participants described Boyle, Charles and Gay-Lussac's Laws as the three gas laws (**Table 4**). In addition, the relationship between microscopic and macroscopic properties of gases, like the relationship between temperature and molecular kinetic energy, was also considered as strong relation conceptual knowledge. About half of the in-service teachers described the general ($P_1V_1/T_1=P_2V_2/T_2$) and one-third of them independently depicted the Ideal Gas Law equation (PV = nRT), and the relationship between temperature and the average molecular kinetic energy (**Table 4**).

Misconceptions

Misconception refers to in-service teachers' incomplete or under-constructed understanding of gases. The extensively depicted misconception of the in-service teachers' description of gases as real and ideal gases are shown in **Table 5**. The in-service teachers failed to understand that an ideal gas does not 'exist' and is only a theoretical model to explain the behaviour of real gases as they had incorrectly categorized gases into two parts, real and ideal gases.

Dimension of Knowledge Structure and Percentage Extensiveness

In response to the second research question, **Table 6** illustrates the knowledge structure and percentage extensiveness in relation to the in-service science teachers' knowledge of gases. The percentage concentration or extensiveness of the in-service science teachers' understanding of the physical properties of gases was shown in **Table 6**. As shown in the table, the factual knowledge dimension was the most extensive (43%) followed by the relational conceptual knowledge (22%). The hierarchical conceptual knowledge dimension (16%) was the least extensive cognitive category. Besides the cognitive dimensions, misconceptions were depicted as a category with extensiveness of 19%.

DISCUSSION

This research explored the knowledge dimensions and misconceptions of in-service science teachers' understanding of gases in preparation to teach physics in high schools. Applying framework thematic analysis and "the structure of the knowledge dimension of the revised taxonomy", three dimensions of cognitive knowledge of gases were obtained (**Tables 2-6**). The result showed that the in-service science teachers' knowledge of gases was predominantly factual rather than conceptual, and that they also held misconceptions (**Table 6**) which needed to be corrected.

The in-service science teachers' concept maps revealed an overwhelming emphasis of gas equations similar to studies that have shown that high-school and university students perform well on algorithmic symbolic problems, but score low on understanding that require conceptual knowledge (Roehrig & Garrow 2007). The dimension of relational conceptual knowledge in gases (**Table 4**) arising from the concept maps may suggest that they might focus primarily on symbolic understanding when teaching the gas laws rather than on the macroscopic and microscopic levels of conceptual understanding and as identified as a problem in other studies (Bilgin et al. 2009; Lin et al. 2000).

The misconceptions of gases suggest that underlying many of their difficulties with the macroscopic variables is often a profound misunderstanding of microscopic models and processes (Kautz et al. 2005). This problem is not unique as even high school teachers hold similar misconceptions of gases and are unable to provide sound explanations of conceptual problems in gas laws (Lin et al. 2000).

The results suggest that the concept maps used were found to be valuable in identifying knowledge dimensions and misconceptions and facilitating learning amongst in-service teachers and science educators. This method can be applied to any knowledge content area that is required to facilitate and support learning. Identification of the four categories of in-service teachers' understanding of gases can now direct science teacher educators to implement appropriate conceptual learning strategies.

CONCLUSION

The analysis of the in-service science teachers' concept maps of the physical properties of gases revealed that they hold different levels/dimensions of cognitive knowledge structure and misconceptions. These are factual knowledge, two dimensions of conceptual knowledge (hierarchical and relational) and misconceptions. The factual knowledge was the most extensive category (43%) while hierarchical conceptual knowledge dimension was the least extensive (16%). Misconceptions were also revealed with extensiveness of 19%.

RECOMMENDATIONS

The results from this study suggest that educators especially in science teaching education programs should not only emphasize factual knowledge but also place more importance on the development of conceptual knowledge. This can be accomplished by providing more opportunities for prospective teachers to clarify their understandings by creating a constructivist learning environment.

Continuous efforts are needed to convince science educators that it is critically important to develop their students' qualitative understanding prior to the quantitative presentation of concepts in formulae form. Thus, the importance of concept-based learning should be emphasized at teacher education institutions. Framework thematic analysis can also support qualitative diagnostic assessment of learning of concepts in specific topics after concept mapping exercises pointing out areas of conceptual knowledge that requires further attention.

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