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The Use of Productive Inquiry in the Teaching of Problem Solving in Chemical Stoichiometry

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Abstract

This paper reports about the use of productive inquiry approach as an intervention in the teaching of problem solving in chemical stoichiometry. The initial method used for this study was the traditional direct lecture. The objective of the study was to explore differences between the two methods when used to teach problem solving among preservice student teachers (PST) in chemical stoichiometry. As indicated the productive inquiry method (PIM) was used as an intervention method and the direct lecture method (DLM) served the role of benchmarking students' conceptual understanding. In effect the study was to observe the functioning of students' knowledge structures on problem solving and subsequently their effect on performance or achievement on the topic. Both the quantitative and qualitative methods were used. The analysis of knowledge structures was based on two perspectives used to describe knowledge, namely, the view that knowledge is theory and it is also made of elements. The findings in this study, varied among students within and across the two methods. Within the methods, individual students exhibited different responses. Across the methods, the PIM produced superior outcomes on students' problem solving. In light of these findings, it can be concluded that students have preferences towards teaching methods or environments. The outcome of this study, suggests the need to mix teaching methods to maximise learning by students with diverse learning styles. Finally, the notion that students have preferences of teaching methods or environments was, confirmed as not all students' problem solving abilities were improved by the use of PIM.

Keywords: *learning environment; productive inquiry; problem solving; knowledge structures; knowledge functioning.*

1. Background and Introduction

Teaching in general and science teaching in particular, is a complex process with unpredictable outcomes. In an attempt to circumvent this challenge, teachers resort to different teaching methods or environments. In chemistry teaching for example, conceptualisation and understanding of abstract concepts, is a challenge to both students and their teachers. Chemical stoichiometry has been found to be one of the topics most students, especially in first-year university classrooms, find difficult to comprehend (Evans, Yaron & Leinhardt, 2008) as it is multi-topic and hence complex and abstract in nature (Johnstone, 2000). In addition to its complex nature, this topic requires students to actively engage in the solving of sophisticated problems. Active engagement requires well organised knowledge structures (Kirscher, Sweller & Clark, 2006; Bledsoe & Flick, 2012) which in most instances first year students do not possess. Challenges such as lack, or poorly organised prior knowledge, call for interventions of different teaching and learning methods or environments. In this study a rarely used teaching approach, *productive inquiry method* (PIM) and the commonly used traditional *direct lecture method* (DLM), were used to explore the problem solving processes students go through and the accompanying effect on knowledge structure changes during learning.

The PIM is found within the spectrum of inquiry-based learning (IBL) approaches. Inquiry-based learning is characterised by unique roles teachers and students play. In using the PIM, teachers engage students actively in the intellectual work of understanding and simultaneously constructing new knowledge. In fact, Dewey views (Cook & Brown, 1999) the PIM as a search that is informed by the use of knowledge, (i.e. students make use of theories, rules concepts within a discipline such as chemistry to construct new knowledge). In other words, knowledge is used to stimulate learning which results in understanding. In inquiry approaches and specifically in problem solving processes, teachers engage students to solve problems (Bledsoe & Flick, 2012). Therefore, lack of relevant prior knowledge may be a disadvantage, as it may limit the level at which a student engages in inquiry activities (p.226). It is therefore, important that students who engage in learning situations where PIM is used, possess sufficient and relevant knowledge. In contrast, in their use of the DLM, teachers (Spronken-Smith, Walker, Batchelor, O'Steen & Angelo, 2008) are responsive, adaptive and stimulate learning through questioning or resolution of problem situations. The DLM makes the teacher a dominant partner in the learning situation, as most of the transformation of the learning material for student learning rests with him/her (Struyven, Dochy, Janssens & Gielen, 2008).

In addition to understanding the problem solving processes that students engage in, this paper aims to establish the effect of the PIM on student learning, in comparison to that of the direct *lecture method*. That is, the PIM is here used as an *intervention method,* whilst the *direct lecture method* serves the role of benchmarking students' conceptual understanding. This study specifically explored the qualitative effect of the PIM on students' *knowledge structures* and their subsequent *functioning* during *problem solving* activities*.* The outcome of the functioning of knowledge structures should be seen as a reflection of their quality. The functioning and effect of knowledge structures were here measured by the general student performance and/or achievement in the chemical stoichiometry topic.

1.1 Research Questions and Objectives

In light of the different outcomes that different teaching methods may achieve, the objective in this study was to respond to two important questions in order to differentiate between the effects of the DLM and the PIM on students' problem solving abilities. It should also be added, that the use of a teaching method or its outcomes depends mainly on the *context* (which includes student perceptions and preferences to different teaching methods) and the *procedures* used. Therefore, the outcomes in this and any other studies are to some extend reflective of these factors.

1.1.1 How did the use of productive inquiry and direct lecture methods affect (if any) students' knowledge structures?

With this question the objective is to establish the effect of the two methods on the quality of knowledge structures. That is, the question aims to establish how student representation or arrangement of concepts was affected and their effect on the ability to relate facts and reason about a problem. That is, did the use of any of the two teaching approaches, in any way affect the manner in which students' related concepts, in constructing understanding and/or generated meaning in their learning?

1.1.2 What was the impact (if any) of both teaching methods on the students' problem solving abilities and subsequently their achievement?

This question is meant to determine the amount of change the quality (e.g. organisation, completeness) of knowledge structures might have had on students' abilities to solve problems and their achievement on the topic. That is, did the quality of their knowledge structures have any significant change (positive or negative) on their ability to solve problems and achievement in general or was it only in relation to specific questions?

2. Related Literature and Theoretical Framework

Generally, the goal of teaching in education is to enhance learning. However, teaching is a complex process that does not always result in the teacher's envisaged learning outcomes (Bodner, 1986). Eysink and De Jong (2012) argue that for learning to occur, the learner must first select and organise relevant aspects of the presented material into a coherent mental representation, and integrate it with other information and his/her prior knowledge (p.584). In this study, a 'coherent mental representation' would be reflected in the student's represented knowledge structures. It should be acknowledged that the knowledge structures need not necessarily be scientifically valid. Students, especially first-year university students, bring their own knowledge structures into the learning situations. They enter the learning environment with different qualities of prior knowledge. It is therefore, imperative that this prior knowledge be known and accurately estimated, before any teaching methods are selected for a particular topic. This makes selection of appropriate methods important to achieve in any particular topic.

There are many methods used in teaching on given topics in science education. Obviously not all methods are appropriate for all topics or in all contexts. The two methods under consideration in this study are examples of some of the methods used in science teaching. The two methods, productive inquiry and direct lecture, were in the current study used to determine their effect on students' knowledge structures and subsequent student achievement in problem solving in chemical stoichiometry. The effect of the two methods in enhancing problem solving abilities of students is here contrasted, because of different procedural activities involved. The PIM (Eysink & De Jong, 2012) as one of the methods in the inquiry learning continuum involves "a more active cognitive engagement for the learner with the learning material," in constructing new understandings or meanings (p.584). That is, to be engaged in a process of productive inquiry requires that one be actively doing things such as *problem solving* or seeking an answer and finding a solution or seeking a resolution to a problem (Cook & Brown, 1999). In contrast with the direct lecture method, the teacher plays a domineering role of directly transmitting information about the contents of the course to *passive* students during a lecture (Struyven, et.al, 2008; Torenbeek, Jansen, & Hofman, 2011).

Although the processes involved in the two methods are different, they may not necessarily yield different outcomes. Struyven et al. (2008) and Entwistle (1991) support this argument, in that students' perceptions of the learning environment are to some extent responsible for the outcomes of their learning and not the context in which learning takes place. This may be due to the amount of direct guidance the teacher provides for the two methods (Baeten, Dochy, & Struyven, 2012). For example, students from poor teaching backgrounds may not have sufficient and relevant prior knowledge to engage in the inquiry method rendering its application ineffective (Kirscher, Sweller & Clark, 2006). These students may not necessarily be comfortable or in favour of the PIM, as it is mostly knowledge dependent (Bledsoe & Flick, 2012). Prior knowledge (Ausubel, 1968) plays an important role in learning, especially where students are themselves responsible for constructing their knowledge, such as in problem solving. Prior knowledge is the domain knowledge that the learner possesses, before the teaching of a particular topic (Gurlitt & Renkl, 2010). In fact, Albanese and Mitchell (1993) posit that for students to succeed in solving problems, they need prior knowledge of the discipline and its concepts or be familiar with the discipline.

Albanese and Mitchell's (1993) prior knowledge requirement to problem solving suggests that individuals with different ways of solving problems have different qualities of prior knowledge and would not necessarily be equally familiar with such problems. This suggestion is confirmed by Bodner's (2003) study on problem solving, in which he found that "a given individual might exhibit fundamentally different behaviours on different problem solving tasks" (p.39). In this study and for the reader's understanding of the specific objective of the study, we describe a *problem* and differentiate it from an *exercise*. Hayes (1980) identifies the existence of a problem when:

- There is a gap between where you are now and where you want to be;
- You are in a state of not knowing how to find a way to cross that gap; and
- There is *also* an element of uncertainty or confusion or ignorance about crossing the gap.

These characteristics describe and summarise the state of an individual who is *unfamiliar* with what is to be done in problem solving. Wheatley (1984) defines problem solving as a process of 'what you do, when you don't know what to do'. When an individual engages in a task s/he is *familiar* with, the process is referred to as a *routine exercise* (Bodner, 2003). Therefore, through the students' process of problem solving, their thought processes may be understood. Wittrock (1986) posits that through the understanding of these thought processes teaching may be better understood and improved. However, this is possible only when we know the effects of teaching upon students' thoughts that mediate achievements. Therefore in this study we focus on the relationship between *structure or organisation* of their prior knowledge and how it *functions* in order to understand these thought processes and eventually students' problem solving processes or strategies. In other words, the study focuses on the concepts and how the student may have used them to construct knowledge or to solve problems in their solutions of chemical stoichiometry problems.

2.1 Theoretical Framework

This study is mostly about the quality of knowledge structures and their functioning in the solutions of chemical stoichiometry problems. It is therefore important to first clarify perspectives through or within which knowledge is described in general and in relation to the knowledge possessed by the student. The knowledge that students possess is here described in two forms. First, it is *intuitive* and *organised* according to the student's way of seeing or doing things. This is what Koponen and Huttunen (2012) refer to as: *knowledge-as-theory*. This is the first window through which it may be assessed and analysed. The second form in which student knowledge is viewed is the fragmented perspective. It describes knowledge as consisting of incoherent and loosely *connected pieces* (diSessa, 1993b). This is the knowledge that through the constructivist learning theory, we may describe student knowledge structures and assess their effect on the problem solving abilities of students.

The constructivist learning theory describes knowledge as the basis on which new learning is constructed (Steffe & Gale, 1995). That is, knowledge is thought of as the *tool* that the learning object uses to construct new meanings in the process of 'knowing' (Cook & Brown, 1999). For example, in problem solving both tacit and explicit knowledge are applied to manipulate information to understand what is required in a problem. What is required in problem solving is to get to the point that one understands the problem (Bodner, 2003). This point is achievable when *knowledge-as-pieces* forms a scientifically valid coherent knowledge structure. This is the stage when the student's knowledge has the coherence and cohesion to recognise and prevent the use of different and conflicting elements of knowledge (Koponen & Huttunen, 2012). That is, this is when students are able to bring together parts of their prior knowledge about the new situation and make sense of what it entails. In addition, for this to happen, the knowledge that the student possesses should be relevant to the problem at hand and well structured or organised (Dochy, 1992). In other words, it must be *transferable* to the problem situation.

The concern for teachers should therefore be on how and which knowledge is used to arrive at a particular answer or even when the answer is not attained, the assessment of the process should lead to understanding the student's processes. How and which knowledge is used gives us the opportunity of understanding the problem solving mechanisms students follow in their learning of specific topics and their effect on problem solving performance. Understanding students' knowledge possession may simplify attempts to understand and enhance students' problem solving strategies or mechanisms. Peackocke (1992) describes knowledge possession as the individual's ability in recognising elements or concepts within a knowledge structure, knowing what these elements or concepts are for and understanding how these concepts work. Knowledge or concept possession should therefore be central to our understanding of students' *problem solving* processes or mechanisms. It controls the *organizing factor* of individuals' thought processes explicitly and tacitly. That is, it relates the *structure* of students' knowledge and its *functioning*. It therefore completes the process of understanding a problem according to Bodner's (2003) 'process of problem solving'.

Our analysis of the student's processes depends on our ability to identify different types and functions of the knowledge that instantiate knowledge possession. That is, it enables us to identify constructs of prior knowledge such as declarative (*recognise a concept*), procedural (*how it works)* and conditional (*what it is for*) knowledge. Declarative knowledge describes the knowledge of vocabulary terms and fact (Marzano & Kendall, 2007). Procedural knowledge describes the individual's ability to perform tasks (Hallet, Nunes, Bryant & Thorp, 2012). Conditional knowledge describes the understanding of *when* and *where* declarative and procedural knowledge are applicable (Alexander, Schallert, & Hare, 1991). Conditional and procedural knowledge (Hallet et. al 2012) are "relationally linked knowledge" types as their function is to define the interrelations among other types of knowledge the individual possesses. These knowledge types are responsible for interactions involved in problem solving or the process of *knowing* as students engage or attempt to solve problems. There is interaction of knowledge structure components (concepts) that lead to knowledge functioning (Smith, 1991). Our understanding of these interactions would therefore ensure that we understand the effect of different teaching methods on student learning and subsequent performance or achievement.

3. Research Methods

3.1 Context of the study

This study was conducted among first-year bachelor of education preservice student teachers (PSTs) at a University of Technology in South Africa. The participants were a cohort studying a Physical Science course, which is a major in their bachelor of education programme. This course is made up of two modules (Physics and Chemistry). A sample of forty seven (47) PSTs participated in the study made up of seven groups of six PSTs and one of five PSTs. The group participants including their group leaders were continuously rotated throughout the six week period of the study. Participants chose a group leader among themselves. The continual changing of group identities was meant to enhance cross pollination of ideas and reduce dominance by high ability students (Collins, 2012). According to Collins, mixed groups enhance representation and increase solution attempts as against homogeneous groups of low ability. The chemical stoichiometry problems that students had to solve were continuously changed at every session and sequenced differently in terms of difficulty and learning outcomes to be achieved.

The study process involved two phases namely, the *generation phase* and *consolidation phase*. In the generation phase participants were given a problem to come up with a solution (Figure 1a).

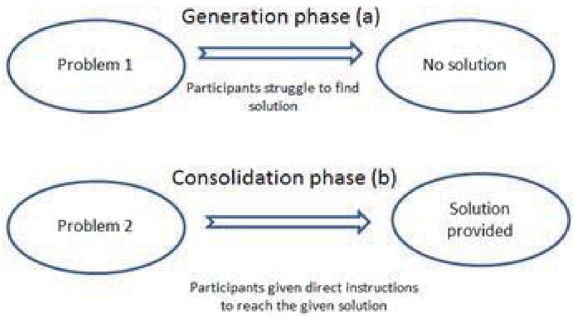


Figure 1: Problem solving processes: generation and consolidation phases, (adaptation from Collins, 2012)

In the consolidation phase participants are provided with the solution which guides their path to solving the problem (Figure 1(b). In addition, participants are given direct instructions of how to arrive at the solution. The two problem solving approaches differ in that one is a 'blind' approach (generation), where participants struggle on their own and the other is a 'leading' approach (consolidation), in which participants may use the solution as a guide (Collins, 2012). It must also be added that as the study progressed participants gained experience and got *familiar* with different approaches to solve a variety of problems in collaboration with different group members. This variety enriches the participants' knowledge and skills in problem solving.

3.2 Research Design

The study was *qualitative and quantitative* and focused on assessing students' problem solving of chemical stoichiometry problems in a Chemistry module. The foci were on assessing the quality of responses and measuring the change in achievement after the two methods were used. Two teaching approaches, the *direct lecture method* (DLM) and the *productive inquiry method* (PIM) were used to teach the same topic (chemical stoichiometry) by the same teacher at different sequential periods. The teaching emphasis was more on problem solving. The DLM was used first in two stages and PIM was used last. It should be acknowledged that there was an *interference effect* on the PIM by the knowledge gained in the DLM. Therefore, the focus would be on the *change* in achievement between the tests after the two methods were used and the final test (transfer test). The main goal of the study was to compare and determine the extent to which each method could have enhanced the quality of knowledge structures for problem solving abilities and subsequently affected *performance/achievement change*. Quality is here determined by the c*ompleteness* of knowledge, knowledge *structure/organisation* and functioning of PSTs' knowledge. The comparison of the methods was both on individual student performances (Figure 3) and on general group performance (Table 1:1; Figure 4)

Participants in the qualitative part of the study were purposely selected. Four PSTs were selected from the two halves (i.e. below and above 50% performances) on the performance distribution table (Table 1.1). In each half of the performance scale two participants were selected from the lower and upper levels because at any stage of these levels participants possess a different and unique type of knowledge. Figure 2 indicates the progressive stages and related teaching methods at which PSTs possessed different qualities and levels of prior knowledge.

That is, PSTs bring or possess different levels/amount and quality of prior knowledge at every stage in their learning. Therefore, the teaching method used would have affected them differently as a result.

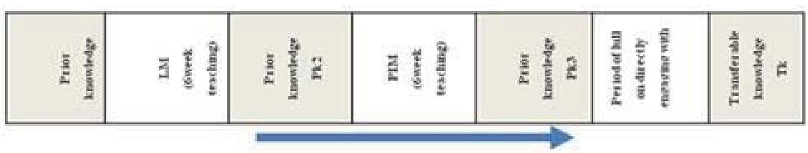


Figure 2: Stages and periods of teaching reflecting PSTs' prior knowledge state and methods

At the start of the study students bring into the learning situation their different general knowledge (Pk1) about the topic. After the lecture (DLM) participants possess a specific and new type of knowledge (Pk2) which may be reliably assessed.

After the use of the PIM the knowledge (Pk2) changes to a different knowledge type (Pk3). This is knowledge *assumed* to have been brought about by the PIM. It is assumed because the contribution of the DLM on the PIM outcomes cannot be reliably accounted for. After a relatively long period (12 weeks) the state of knowledge of students' meaningful learning or transferred knowledge (Tk) was assessed. This knowledge could have changed in any direction considering the time that lapsed between its initial assessment and the post-test assessment. This is the final knowledge students possessed on the topic at the end of their academic year. The three states of their knowledge and the change from their initially assessed knowledge as well the final knowledge are reported and analysed in this study.

The knowledge that one possesses at a particular instance has a bearing on the facilitation or inhibition of his/her learning (Dochy, 1992). It should also be added that for accurate determination of the changes in achievement, it was important to establish PSTs' initial knowledge, before any teaching of the topic could be undertaken. However, in the current study, the initial prior knowledge was not determined as it would have been an unreliable reflection of the students' knowledge on this topic, because of their diverse schooling backgrounds. These were first-year students from different teaching and learning backgrounds, which historically, were mostly disadvantaged in terms of human and physical science teaching resources. In addition some may not have been exposed or taught this topic, as it may not have been part of their curricula or their teachers could not have had time to teach it.

Data for this study was based on a *pen and paper test* of chemical stoichiometry problems ranging from simple to complex (or integrated) problems. The analysis focused on *text* of their responses and the changes in achievement on the topic at three (Pk2, Pk3 & Tk) different stages of assessment. Assessment for both the pre (Pk2) and post-tests (Pk3) were based on the *same test* assessed under the same conditions. The transfer test (Tk) was different as it was meant to assess *transfer* of knowledge from both methods. For data analysis the *cluster analysis method* (Morey, Blashfield & Skinner, 1988) was used.

4. Results and Findings

The results in this study are reported to reflect the effect of the two methods as the outcomes of quality of knowledge structures and achievement. The results are both quantitative and qualitative. The qualitative part was meant to indicate the *structure/organisation and functioning* of PSTs' knowledge structures. That is, they indicate effect of quality of knowledge structures on the workings/functioning of the elements of students' knowledge structures. The quantitative part reports about the effect of these structures on the achievement. However, achievement is here quantified on the basis of the *number of participants* and the level of achievement (in %) between the two methods. The quantitative outcomes of the methods are then related according to the number of PSTs' performance/achievement (Table 1:1; Figure 3) at any instance of the achievement scale. That is, the table (Table 1:1) and figure 2 show the distribution of PSTs according to achievement/performance range for the two methods (DLM and PIM) and the effect on transfer knowledge achievement (TKA).

Table 1:1: Comparison of the number of participants' test outcomes from DLM, PIM and TKA

Performance Distribution (%)	DLM	PIM	TKA	Comment
0 to 10	6.4 %(3)	4.3 %(2)	4.3 %(2)	Most PSTs are found under the **DLM** column than in any of the three columns
11 to 20	21.3%(10)	2.1%(1)	6.4 %(3)	
21 to 30	19.1 %(9)	4.3 %(2)	8.5%(4)	
31 to 40	21.3%(10)	8.5%(4)	17.0%(8)	
41 to 50	10.6%(5)	8.5%(4)	23.4(11)	
% of **PSTs** obtaining marks below or equal to 50	**78.7%(37)**	**25.5%(12)**	**59.6%(28)**	50% is used as a threshold as it determines if a **PST PASSES or FAILS**
51 to 60	8.5%(4)	6.4 %(3)	21.3%(10)	Most PSTs are found under the **PIM** column than in any of the three columns
61 to 70	6.4%(3)	8.5%(4)	14.9%(7)	
71 to 80	2.1%(1)	21.3%(10)	2.1%(1)	
81 to 90	4.3 %(2)	14.9%(7)	0.0%(0)	
91 to 100	0.0%(0)	8.5%(4)	2.1%(1)	
% of PSTs obtaining marks above 50	**21.3 %(10)**	**74.5%(35)**	**40.4%(19)**	

Comparison of the three graphs (Figure 3) shows a varied distribution of PSTs' performances on the three situations of assessment. For the DLM, majority (78.7%) of PSTs' achievement is *below* the 50% mark, whereas majority (74.5%) of the PIM PSTs are *above* the 50% mark. The TKA marks at both levels (i.e. above and below 50%) are between the DLM and the PIM achievements. The DLM performance is in all instances (only 40.4% of PSTs obtained above 50% and 59.6% obtained below 50%) of comparison below both the PIM and the TKA. Among the three distributions (Figure 3) the PIM shows a *better* distribution in terms of the spread of achievements. The TKA has most of the PSTs' achievements (59.6%) in the lower end of the mark distribution. On the other hand, the DLM has the least PSTs' achievements (21.3%) in the upper level of the performance distribution.

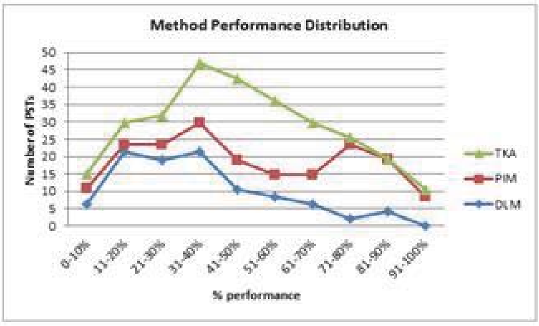


Figure 3: Distribution of PSTs in terms of achievement/performance

The analysis of outcomes of the two methods and the analysis of the *transfer* assessment show conclusively that there is generally a difference between the initial achievement test (after DLM) and the two post-tests (after PIM and TKA). The differences show a positive change in achievement for most of the PSTs in the PIM from the initial assessment. However, i*ndividual PSTs' achievements were varied.* There were those who dropped in their achievement and those who drastically improved their initial performances (Figure 4).

The following are some of the reasons that may explain these individual achievement changes:

- First the fact that students were *familiar* with this test may be the main contributor to the achievement demonstrated in the PIM (Bodner, 2003)
- The second reason could be the prior knowledge gained in the first test. That is, this prior knowledge has a facilitating effect (Dochy, 1992) and could have enhanced their conceptual understanding when engaged in the PIM. This knowledge was necessary because the PIM can only function well with some topic specific prior knowledge and
- Generally, students bring into the learning situation varied quality and amount of prior knowledge. These will vary their performances or functioning of their knowledge structures (Dochy, 1992).

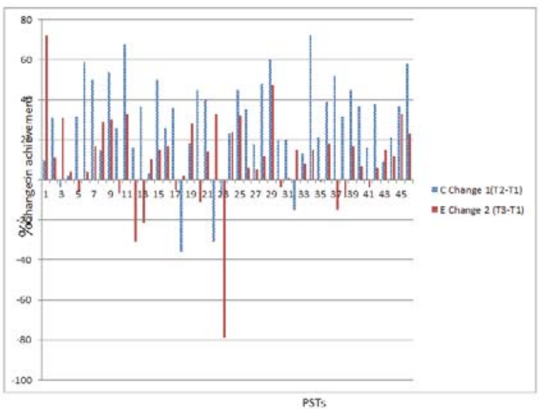


Figure 4: Individual achievements between DLM and PIM (T2-T1) and between DLM and TKA (T3-T1)

From the discussion so far, it is clear that there is a general *positive* change as a result of the PIM. Although there have been some PSTs whose performances dropped, the trend is that in this study *the PIM approach yielded beneficial outcomes for the majority of students*. Therefore the main finding of the quantitative analysis is conclusive as to which method yielded positive results. The limitation of the study is mainly due to the fact that the initial prior knowledge could not be determined. This would have allowed a determination of the amount and quality of prior knowledge that advantaged the performance in the PIM. That is, an accurate determination of the differences between the two would have been achieved.

4.1 Comparing specific student knowledge structures and their functioning

The qualitative analysis in this study involved four purposely selected PSTs. The selected PSTs represented each half of the percentage distribution levels. That is, the lower and upper achievement levels were represented. Text analysis of the four PSTs showed some changes in PSTs' approaches to problem solving as a result of the teaching methods. Excerpts and solutions to problems from the test scripts were `used to demonstrate the changes for each participant. In addition to the content of their responses their achievement marks were indicated. Analysis of the excerpts and PSTs' solutions to problems is at two levels namely the *manifest and latent content analyses* (Graneheim & Lundman, 2004). The manifest content analysis focuses on the *visible* and *obvious* components of what the text says. In fact, this analysis' focus is on the "knowledge-as-theory" part of the student's knowledge or the macro changes in the student's knowledge. The latent content analysis on the other hand deals with the "relationship aspect and involves an interpretation of the underlying meaning of the text" (p.106). This analysis focuses on the "knowledge-as-pieces" aspect or the impact on knowledge functioning. The analysis of the "knowledge-as-pieces" is at the micro level and takes a deeper look into individual elements (concepts) of the knowledge structure and their relationships. Generally, analysis is on the process (indicated by text) the PSTs used to solve the problems at hand. Text and the steps of the process are analysed against the expected and valid answers. The PSTs interpretations are also assessed as part of their problem solving processes.

4.2 Summarised interpretation of underlying meanings from the two individual PST responses

Manifest content analysis: In the first test (after DLM) this PST's (PST 1) knowledge is limited to solving simpler problems. The problem (1.5.1) is simpler because there are no conversions required. In the second part of the problem the student's 'coherent explanatory system' is evident even if it is not scientifically valid. However, this system could not help in solving the problems (1.5.2 and 1.5.3). These problems require manipulation and conversions of mass to moles and the resolution of the problem. In the second test (i.e. after PIM) the student shows development and organisation of elements within his/her knowledge structure. A coherent theory is evident in the approach to problem solving. The student shows familiarity with the processes of problem solving.

4.3 Latent content analysis

The difficulties that the PST encountered in the attempt to solve the problems under DLM may be attributed to poor structural organisation of his knowledge. That is, the PST's knowledge structures appear less organised. In addition there is evidence of an incomplete relevant prior knowledge to resolve the problem. According to Peackocke (1992) one's knowledge possession is the ability to recognize a concept, know what it stands for and how it works. Some of these elements (e.g. knowing how the concept works) were missing in this student's knowledge structure. However, in the second test (after PIM) the student could not solve the whole problem but there was evidence of structural development.

Question 1.5

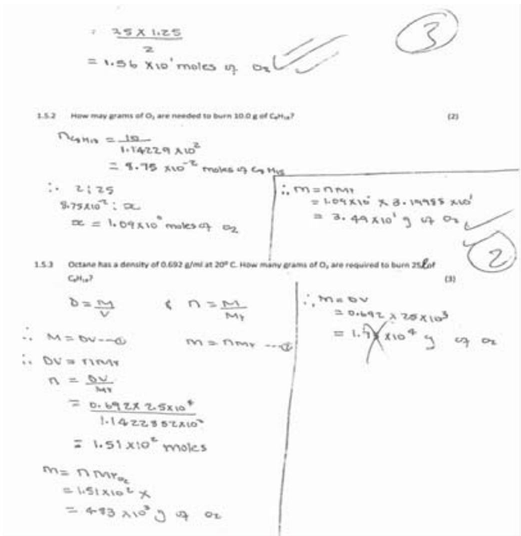
The complete combustion of octane C_8H_{18} proceeds as follows:

$C_8 H_{18}$ (l) + O_2 (g) → CO_2 (g) + H_2O (g) (The equation is not balanced)

- How many moles of O_2 gas are required to burn 1.25 moles of C_8H_{18} (l)?
- How many grams of O_2 gas are required to burn 10.0g of $C_8 H_{18}$ (l)?
- Octane has a density of 0.692g/ml at 20°C. How many grams of O_2 gas are required to burn 25l of $C_8 H_{18}$ (l)?

PST 1 DLM (54%):

PST 1 PIM (90%):



4.4 Summarised interpretation of underlying meanings from the two individual PST responses

4.5 Manifest content analysis

This student has a *coherent framework of theory*. However, there is a problem in describing and representing (symbolically) the concepts and balancing of the equation in the first test (after DLM). Inability to represent chemical formulas affects problem solving processes. This was the case with this student. The idea was evident but organisation of elements was the cause of failure. That is, the student could not pass the important huddle (writing and balancing of equation) of chemical stoichiometry. Without this part of the process being correctly written, it would be impossible to solve this problem. The student encountered the same problem in the second test (after PIM).

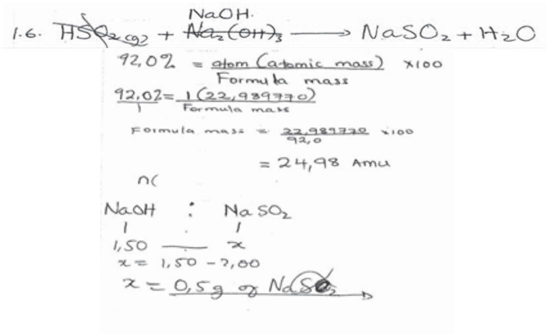
4.6 Latent content analysis

One important observation about this student was the inability to reorganise existing knowledge. It was also evident from the response in the second test (after the PIM) that there was no structural change in the student's knowledge. That is, the same student's theory still existed as in the initial test. There was an apparent incoherent organisation of the facts about the concept of *percentage yield* and its calculation. That is, the use of atomic masses clearly shows that the student's mole concept and molar relationships based on a balanced chemical reaction was not well understood. The student's knowledge was incoherent and therefore not functional to construct understanding. The student was clearly focussed on using a *memorised* equation for *percentage yield* without the understanding of what the question was all about.

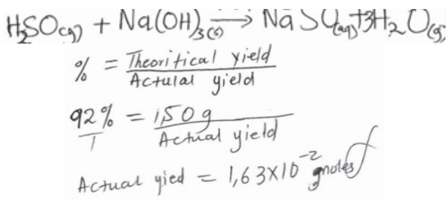
Question 1.6:

Hydrogen sulphide is bubbled into a solution of sodium hydroxide. The resulting solution is sodium sulphide and water. Determine the mass (in grams) of sodium sulphide formed from 1.50 grams of hydrogen sulphide bubbled into a solution containing 2.00g of sodium hydroxide. The amount of sodium sulphide formed is 92.0%.

PST 2 DLM (25%):



PST 2 PIM (43%):



4.7 Summarised interpretation of underlying meaning from the two individual PST responses

Manifest content analysis: The challenge of this question is in the ability to apply the knowledge of the mole concept. The student managed the first part of calculating the moles of the products. This suggests limitation in his theory. That is, his theory in the first test (after DLM) was calculation of moles of compounds. It is apparent from the response, that the student could not separate the moles of the individual atoms of carbon and hydrogen from these products.

In the second test (after PIM) there is a sign of development of his theory though not necessarily accurate or valid.

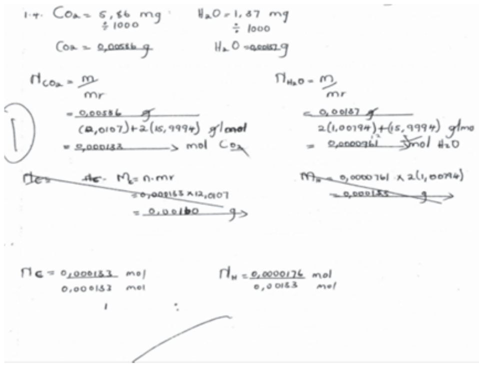
4.8 Latent content analysis

Ausubel's (1968) notion that the amount and quality of the knowledge that one brings into the learning situation determines the extent to which one can learn holds true for this student. The marks achieved (20%) in DLM show that it would have been difficult for this student to do well in the tests that followed. The knowledge possessed by this student lacks most of the characteristics described by Peackocke (1992), although the basic one of identifying the mole concept existed as shown by the calculation of moles of the products. The student's knowledge can be said to be incomplete as he/she could not complete solving the problem. The notion of familiarity as described by Bodner (2003) did not hold for this student. However, there is some semblance of a coherent and organised explanatory system.

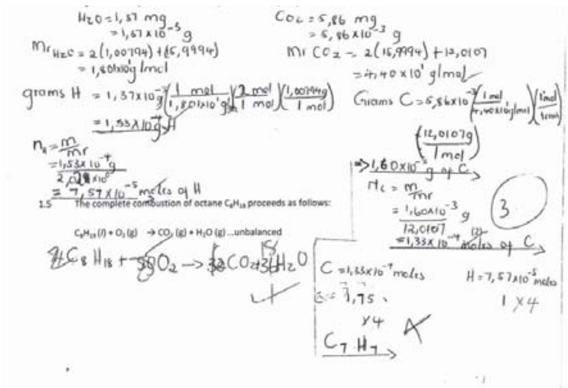
Question 1.4

Combustion analysis of toluene gives 5.86 mg of CO_2 gas and 1.37 mg of water. If the combusted compound contains only carbon and hydrogen what is its empirical formula?

PST 3 DLM (20%):



PST 3 PIM (35%):



4.9 Summarised interpretation of underlying meaning from the two individual PST responses

Manifest content analysis: This student managed to correctly answer the first two questions (1.5.1and 1.5.2) but could not answer the third (1.5.3). It appears the more complex (that is involving more than one concept) the question becomes the more difficult it appears for the student. The student could not relate the density and the moles in order to determine the mass in grams of the O_2 gas required to burn the 25*l* of toluene. That is, the PST could not use density to calculate the mass of 25*l* toluene. The student's knowledge is incoherent and cannot be used successfully.

4.10 Latent content analysis

The difficulty to solve complex problems stems from lack of well organised or coherent knowledge and in some instances incomplete knowledge. In this instance, the student could identify the concept of mole but could not use the concept of density to determine the moles and then the mass. Given the volume and density, one should be able to derive mass from the relationships. Without a well structured knowledge base knowing what and how concepts work may be difficult. That is, it becomes difficult to access such knowledge (Dochy, 1992). In addition, it may be that this was the case as the student (as demonstrated by performance, 18%) possesses poor quality knowledge or the possessed knowledge is limited.

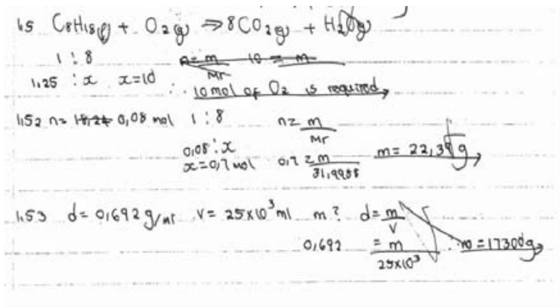
Question 1.5

The complete combustion of octane $C_8 H_{18}$ proceeds as follows:

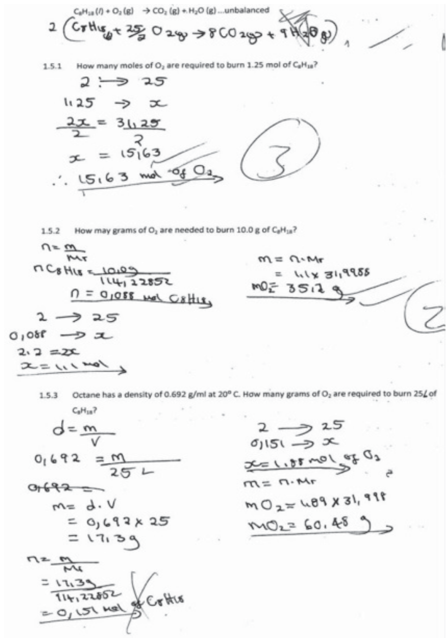
$C_8 H_{18}$ (l) + O_2 (g) → CO_2 (g) + $H_2 O$ (g) (The equation is not balanced)

- *How many moles of O_2 gas are required to burn 1.25 moles of $C_8 H_{18}$ (l)?*
- *How many grams of O_2 gas are required to burn 10.0g of $C_8 H_{18}$ (l)?*
- *Octane has a density of 0.692g/ml at 20°C. How many grams of O_2 gas are required to burn 25l of $C_8 H_{18a}$(l)?*

PST 4 DLM (18%):



PST 4 PIM (63%):



5. Discussion and Conclusion

The purpose in this study was to compare the two teaching methods or environments. According to Entwistle (1991) students' perceptions of the learning environment has much influence on how they learn and not necessarily the learning context. The fact that students perform differently under different methods, should therefore not be ascribed to the method, but rather to their perceptions of such methods. The fact that within the two methods the effect on students' problem solving abilities appears to be varied supports Entwistle's argument. This was to be expected as students enter the learning situation with different prior knowledge, experiences and school teaching backgrounds. Although this is the case there is a general trend as to how the two methods affected students' problem solving abilities.

5.1 How did the use of productive inquiry and direct lecture methods affect (if any) students' knowledge structures?

This question was clearly answered by the quantitative analysis. There is a general trend in the result (Figure 3) suggesting that the PIM produced *better* quality of responses and subsequently improved students' problem solving abilities. It should also be added that the influence of the *prior knowledge* on the performance, may have played a significant role in enhancing achievement within the PIM. This aspect could not have been avoided in any study of comparing methods if the same students were to be used, where one of the methods (PIM) depended on students requiring some basic knowledge of engaging in this method (Collins, 2012). That is, students were exposed to this method after having been taught by the DLM earlier. Therefore, this method (PIM) may have been advantaged by the DLM, although this was not the case for all students. Students have preferences of learning environments and for students whose performance did not improve, may be due to the fact that they do not necessarily prefer the inquiry approach (Struyven, et.al 2008). The last test (TKA) was meant to *validate* the result or to assess if the new knowledge structures were sustainable. The result of the TKA confirmed this was the case as the result was generally still better than the DLM.

5.2 What was the impact (if any) of both teaching methods on the students' problem solving abilities and subsequently their achievement?

In this question, the purpose was to determine the impact the quality of the knowledge structures might have had on students' ability to solve problems. That is, did the quality of their knowledge structures have any significant change in their ability to solve problems in general or was it only in relation to selected questions? The effect was varied because individuals would have different ways of solving problems as they would not be equally familiar with such problems or have the same prior knowledge (Albanese & Mitchell, 1993). Generally, the quality of knowledge possessed by an individual affects the ability to use such knowledge. In this study students' initial knowledge has had an impact in their ability to respond positively to some of the questions in the test, especially complex problems. Students with poor quality knowledge, tended to find it difficult to answer most questions, especially multi-concept questions. Students with an initial better quality prior knowledge tended to do well in both the DLM and the PIM. Those who did not do well in the DLM test but improved the quality of their knowledge structures, did well in the second (PIM) and third (TKA) tests. This is because various factors affect how well students learn, especially in the consolidation phase (Collins, 2012).

From the outcomes of this study, one can conclude that variety in teaching methods generally and specifically in the teaching of complex topics such as chemical stoichiometry is, imperative. There is therefore the need to encourage the use of multiple teaching methods within or across subjects. This would in turn accommodate different students' learning styles and/or students with different entry level prior knowledge. Considering the positive difference productive inquiry brought to the quality of students' knowledge and performance in this study, one would be tempted to recommend its use (as a complementary method) in subjects as complex and abstract as chemical stoichiometry. In addition, in using productive inquiry, we need to accurately document the roles of students' and their teachers when the methods are applied. That is, we need to account for every process and outcome of our methods.

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