The Challenges of Promoting and Assessing for CONCEPTUAL UNDERSTANDING IN CHEMICAL ENGINEERING

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Engineering education literature abounds with research-based advice on teaching methods that promote better quality learning among students.[e.g.,1,2] Recommendations often include reducing content coverage, promoting active learning in the classroom, and using assessment methods that require students to demonstrate a high level of understanding and ability. This paper concerns a second-year chemical engineering course in which recommendations such as these were adopted and presents an in-depth investigation into the influence of the course environment on students' approaches to learning. (This research project is discussed in more detail, from an educational research perspective, elsewhere.[3-5]) This paper focuses specifically on the important implications that this work has for chemical engineering educators and their practice.

Approaches to Learning

Approaches to learning, first identified in a landmark study by Marton and Säljö,[6] describe both *what* students do when learning and *why* they do it. The fundamental distinction is between a deep approach, in which students aim to understand what they are learning, and a surface approach, in which this motivation is not present. Some studies, including the present one, have also identified variations of the deep and surface approaches particular to certain contexts.[e.g.,7] Approaches to learning are not stable individual student characteristics, but rather are assumed to be fundamentally influenced by the educational context in which students find themselves.[8]

The pedagogical implication of this research is that teaching should be designed to elicit deep approaches to learning.[9] It is important not to confuse approaches to learning with learning styles. Learning styles describe characteristics of learning that remain fairly stable across multiple contexts (sensing vs. intuitive perception, visual vs. verbal input, deductive vs. inductive organization, active vs. reflective processing, and global vs. sequential understanding). Learning styles research leads to a focus on teaching methods that can match the diversity of learning styles in a classroom.[10]

We suggest that learning styles and approaches to learning should be considered as complementary theories on learning, and that the choice of theory be determined fundamentally by the focus of the research and development. In the present study, we were most concerned with promoting conceptual understanding among students, and the theoretical framework offered by the work on approaches to learning (which emphasizes whether or not students are focusing on understanding) was therefore considered to be most appropriate.

The role of students' perceptions in determining their approaches to learning is emphasized in the work of Ramsden.[8] He points out that it is not the course context as defined by the lecturer that influences a student's choice of approach, but rather the way the student perceives this context. Students' perceptions are far more likely to be influenced by the "hidden" curriculum that describes what has to be done to pass the course[11] and the "cues" that lecturers give out in

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The second . . . finding was that unless students were already using a conceptual approach at the start of the course, they were unlikely to make a change to it despite explicit attempts by the lecturers to foster development of such approaches.

this regard,[12] than the formal curriculum comprising the official aims and objectives of the course.

Metacognitive Development

The notion of metacognition arose in the context of information processing studies in the 1970s, and is described by Baird[13] as "the knowledge, awareness and control of one's own learning." Metacognitive development can therefore be described as a development in one's metacognitive abilities, *i.e.,* the move to greater knowledge, awareness, and control of one's own learning. Metacognitive development has been used extensively as a theoretical position in (mainly school-based) science education research in order to describe and promote better-quality learning outcomes.[14] The present study introduces the explicit conceptualization of metacognitive development as a shift in one's approach to learning.

MATERIAL AND ENERGY BALANCES COURSE

As is common in many chemical engineering programs around the world, the first major chemical engineering course encountered by students at the University of Cape Town is the material and energy balances course. Not only does this course have a history of high failure rates, but frequently even those students who pass the course display poor mastery of the fundamental concepts in subsequent course. In 1998, the lecturer responsible for the course was motivated to do something about this long-standing problem, and, inspired by the literature on student learning and innovative teaching methods,[e.g.,2,15-18] she selected and implemented new approaches to teaching, assessment, and curriculum. The chief objective of the changes was to promote development of students' conceptual understanding and metacognitive abilities, in addition to the existing (and previously almost exclusive) focus on the development of problem-solving skills. These changes were implemented in 1998 and were fully in place in 1999 when the present study took place.

Curriculum Content Reduced

Overloaded curricula are common in engineering courses worldwide[19] and the material and energy balances course was no exception. Inspired by the maxim "Cover Less, Uncover More," the lecturer decided that in order to achieve her aim of teaching and assessing for "deep" understanding, the amount of material would have to be reduced. Following a workshop held with staff to decide on critical outcomes for this course,[20] the content was reduced by approximately 25%.

TABLE 1
Fieldnotes: Observations of Lecture

Friday 23 April 1999 (Research Logbook, pgs. 52-53)
In this morning's lecture Dr Barnes got the various groups to give feedback on the different types of heat capacity data they had used (in a group exercise started in the previous lecture). She got the groups to focus in their feedback on the method they had used. Jane and Amina gave great feedback on how to use mean molar heat capacity. Then the class joker, James, reported on the polynomials—and engendered much mirth by scribbling on the board something that was actually incorrect. Dr Barnes then corrected him, at which he made a marginally better attempt. It was interesting that sometime at this stage Geoff (from the same group) gave an explanation from the floor of what needed to be done, which was very good. David reported on the graphical method—although he started writing up long equations which was a bit odd seeing as they hadn't used these. John then gave great feedback on using [mean] molar heat capacities—with a good method to get around the problem. Dr Barnes then asked the class which method they would prefer—and hopefully the case for mean molar heat capacities was made. Dr Barnes then got them to do exercise 1 to practice using heat capacities in energy balances. At the start she gave students time to puddle around [experiment] in it—and then got someone to give the energy balance for this problem. Tim asked whether 100 kmol/s didn't imply the need for a $0.5v^2$ term—and she explained why not. She then went into solving the problem on the board. I was surprised that she used the polynomial method after having lauded mean molar heat capacities earlier on—but maybe just for practice I suppose. Students were asked to try exercise 2 for homework, which she will go through in class on Monday.

Teaching for Active Learning

The teaching strategies adopted for the course were designed to get students to engage actively with concepts, something that is surprisingly uncommon in undergraduate science and engineering lectures.[e.g.,9,21] A typical "lecture" involved the lecturer posing questions to students, getting them to try problems on their own, and then discussing their work with classmates and reporting back to the class. In these reportbacks, the lecturer would get students to compare and evaluate different responses, and where appropriate she provided fresh input or comments on their work. An extract from the first author's fieldnotes on a typical lecture is shown in Table 1.

The lecturer also communicated a shift in emphasis away from the lecture providing everything that was needed to succeed in the course toward an expectation that significant learning would take place in the tutorials and at home, both individually and with classmates. Tutorials are problem classes lasting two to three hours in which students work through a set of problems, with the lecturer and tutors available to help them. The lecturer introduced a set of weekly journal tasks into the course to promote students' reflection on their understanding of concepts and their metacognitive development.[22,23] Two of these tasks are reproduced in Table 2.

Assessment for Understanding

The lecturer was concerned that the pre-1998 question format in the course (traditional numerical problems) did not adequately assess students' conceptual understanding. She therefore worked on developing items that were non-numerical and which assessed conceptual understanding.[24] Initially she focused on separate "short questions," but then started adding "Explain why..." and "What if..." questions onto standard problems. She also altered some multistep numerical problems so that students had to explain what they would do rather than performing the actual calculations. These items comprised approximately a fifth of each test and examination. A sample item with conceptual components from the second class test in 1999 is provided by way of illustration in Table 3. Other innovations in the assessment domain included a "crib sheet" that students could bring to tests, on which they could write anything they wished. The lecturer also introduced an "unlimited time" format for one of the class tests in order to emphasize the importance of understanding over working fast.

TABLE 2
Samples of Journal Tasks

Week 5: Journal Task
Reflecting on the first class test.

1. Give a general analysis of your performance in the test.
   - You may wish to calculate your % mark for each question
   - Recall how you felt before and after the test.
   - Are you happy with your performance in this test?
   - Do you think your mark reflects your understanding of the material?
2. Identify your weak and strong points as displayed in this test performance.
3. What are the most important lessons that you have learned from this text? Is there anything that you need to do differently from now on?

Week 8: Journal Task

1. Go back through all your notes and problems so far on energy balances. Find two concepts (or definitions or equations) that you don't understand OR are not too sure of OR would like to find out more about. Write them down.
2. Now go to the recommended texts for this course (Himmelblau, Thompson & Ceckler, Felder & Rousseau, Reklaitis), and look to see if there is anything there to help you with the two problems you have identified above (make use of the contents page, the index, and general browsing to locate a topic). If you haven't found anything to clarify these problems, find a classmate or tutor to lecturer to help you.
3. Make some notes on how you have resolved your confusion. You must clearly state what you have discovered your problem to be and how you have resolved it. Don't just write out a paragraph from the textbook!
   NOTE: This is not an easy task to do properly. You need to make time to seriously think about what you do understand and what you don't understand. If you take the time for this task, you should be able to progress significantly in your understanding. Merely copying out notes on a topic will not be considered a satisfactory response to this task—the task requires you to think about your own learning of energy balances.

METHODS OF DATA COLLECTION AND ANALYSIS

The aim of the research project was to investigate students' experiences in this restructured course environment—specifically to uncover their approaches to learning and to what extent, and why, these changed over the duration of the course. The methodological position adopted in the study was largely informed by "naturalistic inquiry".[25] This research paradigm has been developed for research involving people in natural settings and is founded on a constructivist epistemology that critiques the apropriateness of the traditional "scientific method" for such research contexts.[26] Although not exclusively, naturalistic inquiry does tend to favor the collection of qualitative data and the use of grounded theory analysis.[27]

TABLE 3
Sample Conceptual Assessment Item

Question 2 ***(10 marks)***
In a recycle process for the production of ethylene oxide, the ethylene:air ratio in the fresh feed is 1:10, the separator is ideal, the recycle ratio (recycle:waste) is 2, and the overall conversion of the process is 75%.

a. Draw a flow diagram depicting the process. Label all streams. *(4 marks)*

b. Your colleague calculates the concentration of N_2 in the recycle to be approximately 80 mole %. Explain, without calculation, whether or not this answer could be correct and why *(2 marks)*

c. Your colleague also calculates the conversion per pass to be approximately 90%. Explain, without calculation, whether or not this answer could be correct and why. *(2 marks)*

d. If the fresh feed rate and the reactor conditions remain unchanged and the recycle ratio is increased to 4, which of the following results is true: *(1 mark)*
   1. The conversion per pass increases
   2. The conversion per pass remains the same.
   3. The conversion per pass decreases.

e. If the fresh feed rate and the reactor conditions remain unchanged and the recycle ratio is increased to 4, which of the following results is true: *(1 mark)*
   1. The overall conversion increases.
   2. The overall conversion remains the same.
   3. The overall conversion decreases.

This methodological position was largely determined by the nature of the research questions in the present study. Given that the forms of the approaches to learning and the nature of student perceptions in this context were largely unknown, in-depth data was required, and this required the use of a small-scale qualitative study rather than a large-scale survey. Therefore, eleven students were selected for the study, using the technique of purposive sampling in which maximum diversity in race, gender, and prior academic performance, rather than statistical representation, was the key determinant of selection.[25]

The key data in the study derive from a series of four individual interviews over the duration of the semester-long course, followed by one or two interviews in the next semester. The interviews were semi-structured, with the general aim of getting the students to talk about their experience in the course as they went along. In addition to the interview transcripts, other data for each interviewee was obtained, such as journal entries, assessment scripts, and classroom observations. The data analysis followed the standard procedure for qualitative analysis.[27]

RESEARCH FINDINGS

Approaches to Learning

Three different approaches to learning were identified in this context:

- A conceptual approach, in which the underlying intention is to understand concepts
- An algorithmic approach, in which students focus on learning solution methods
- An information-based approach, which emphasizes gathering and remembering pieces of information

The conceptual approach is closely related to the deep approach identified by Marton and Säljö.[6] The information-based approach is very close to their surface approach. The algorithmic approach may be thought of as an advanced form of surface approach, and particular to quantitatively based disciplines. At first glance it may appear that these approaches equate to the first three levels (although not in that order) in Bloom's well-known taxonomy (knowledge, comprehension, application, analysis, synthesis, and evaluation).[28] It is possible that in some respects the knowledge level implies at least an information-gathering approach, and the comprehension level a conceptual approach, but while Bloom's application level implies comprehension, the present algorithmic approach is defined as not involving the prerequisite understanding. We would therefore suggest that the taxonomy is not comparable to the set of approaches to learning identified in this paper.

These approaches are illustrated by the following quotes:

Conceptual

> *I just hate it when I do something and I can't understand exactly what it is I'm doing. I'd rather leave something and not do it than do it and not understand what I was doing. (Thabo, Interview 5)*

Algorithmic

> *And the thing is, I probably didn't understand, not totally, but often I didn't quite have an understanding of the process, I just knew how to do the calculations... (Geoff, Interview 2)*

Information-Based

> *I have to go over my notes again, I go over them sometimes, not like after each lecture and stuff, so it's like very important because I seem to forget like the small definitions and stuff. And the way they all apply, and...I sometimes just forget the whole thing. (Shahira, Interview 4)*

When reflecting on the course, most students described a dominant approach, or attempts to shift from one approach to another. These approaches are represented in Figure 1. It can be seen that four students made predominant use of a conceptual approach from the start of the course. Together with another student who shifted to this approach very early on (and who seemed to have considerable previous experience of such an approach), these were the five students in the interview sample who were successful in the course. It therefore appeared that the course was in fact assessing conceptual understanding, as had been planned. But the lecturer had also hoped to support metacognitive development, and it seemed that this aim was not met. Of the seven students using non-conceptual approaches at the start of the course, there was only one who managed a clear shift to a conceptual approach during

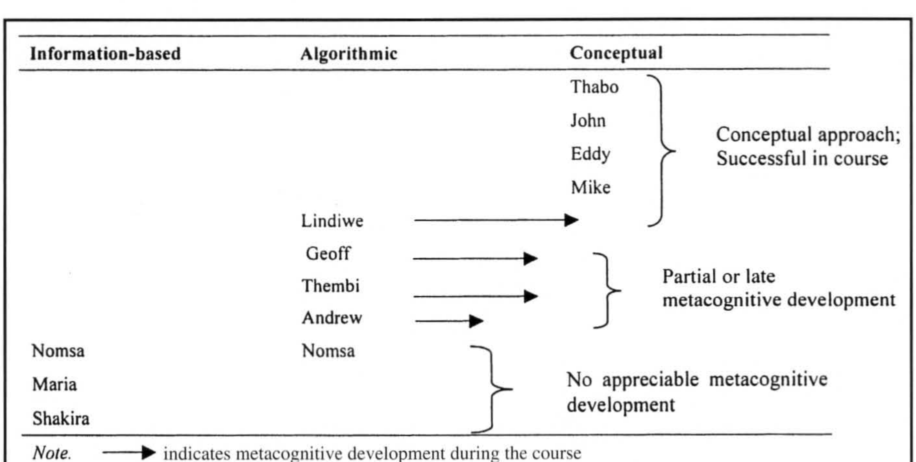

***Figure 1.** Summary of individual approaches to learning.*

the course. The remaining six students displayed partial, late, or no metacognitive development; this experience was referred to as "limited metacognitive development."

Metacognitive Development

This study then focused on the six students who had not managed to substantially use a conceptual approach at any stage in the course. Of particular concern was that the three students using predominantly an algorithmic approach had shown significant awareness of the deficiencies in their approach and at times made genuine attempts to change their approach, but they were unsuccessful in these attempts over the duration of the course. Two of these students did manage to seriously engage with a conceptual approach during their preparation for the re-examination (students who failed the course are allowed a second final examination), but this was too late to build sufficient conceptual understanding. The question we needed to address was why this metacognitive development had been so limited. This was done through an exploration of key aspects of students' perceptions of the course content.

A dominant aspect of students' perceptions of this course concerned time pressure. This was noted both in the workload outside class (deriving mainly from tasks set in other courses taken in the same semester) and in tests and examinations. All students noted the experience of time pressure, yet there were the following significant differences between those using conceptual and those using non-conceptual approaches:

- ***Conceptual Approach:*** *Students' recognized that although using a conceptual approach was costly in terms of time, it was essential for success in the course, and actually in the long run would save time.*
- ***Non-Conceptual Approach:*** *Students avoided the conceptual approach, feeling that there was not enough time available (which led to a vicious cycle when, after failing to develop conceptual understanding, they experienced even more time pressure and were even more inclined to feel there was not time for using the conceptual approach).*

The close relationship between perceptions of time and approaches to learning is clearly illustrated in the following extracts from interviews with Geoff, who in week 11 was using an exclusively algorithmic approach, but by week 2 of the second semester had shifted to working with a conceptual approach.

Geoff: Week 11, first semester (preparing for test 3)

And I don't think I have the time. I don't know—one thing looks like an exercise—I might do that, as practice. But to sit and think, at the moment I don't have time to do that.

Geoff: Week 2, second semester (preparing for re-examination)

Whew! I'd say do a difficult problem and spend some time on it and try and get out of it as much as you can. Like understand the percentage conversion, understand where you took your reference points from and why, and how did you get that answer.

In summary then, this study has produced the following findings. Three approaches to learning have been identified: conceptual, algorithmic, and information-based. Only the conceptual approach was related to the required learning outcomes on this course. Even though the educational context had a strong focus on metacognitive development, very few students managed to shift significantly toward the use of a conceptual approach during the course. This limited metacognitive development appeared to be related to time pressure, both out of class and during tests and examinations. For students using non-conceptual approaches, their perception of time discouraged the adoption of a conceptual approach.

DISCUSSION

The course objectives centered on the development of conceptual understanding and metacognitive skills. From this study it has been seen that conceptual understanding (obtained through use of a conceptual approach) was a necessary and sufficient condition for success in the course (at least for the students in the sample). It would therefore appear that the combination of standard numerical and conceptual non-numerical questions did indeed facilitate testing for conceptual understanding.

With regard to the course objective to promote metacognitive development, the study shows that the only students to have made successful use of a conceptual approach were those who were already using such an approach. Furthermore, many of these students appeared to have significant prior experience of such an approach. Other students became aware of the need for a conceptual approach and made attempts to shift to it, but it appeared that the broader context did not fully support this development. From this we can see that requiring a conceptual approach and supporting metacognitive development toward such an approach are two entirely different things. The course, as it ran in 1999, seems to have been more successful at the former than the latter. Seen against the research literature on student learning and metacognitive development, these results could be expected. There are countless studies that point to the extreme difficulty of achieving metacognitive development, or in other terms, changes in approaches to learning.[29-32]

The findings of this study can also be viewed as a clear illustration of Ramsden's[8] premise that the way a lecturer perceives a course is not necessarily the way students perceive it, and that this has a significant influence on the quality of student learning. This material and energy balances course was explicitly designed to foster metacognitive development, with frequent overt mention of learning processes in class, significant use of peer discussion in lectures and tutorials, and a series of journal tasks aimed at conceptual understanding and metacognitive development. What many students perceived as the salient features of the course context were the time pressure and the need for time management. Even though they engaged in journal tasks and discussions, the focus of these students was on learning to work fast. The outcome of these "mixed messages" was that students focused overwhelmingly on the message given out by the time-pressured context rather than the formal message about the importance of developing a conceptual approach given in the course outline and in lectures.

It is important to note the differences between the two different surface approaches[6] identified in this study: the algorithmic and the information-based approaches. Only students using an algorithmic approach showed any appreciable (even if partial) metacognitive development during the course. It would therefore seem that although the algorithmic approach is not the most desirable approach to learning in a context that requires conceptual understanding, it could be considered at least more productive than the information-based approach. This echoes the work of Niaz[33] in chemistry education, who suggests that using algorithmic reasoning might facilitate a transition to conceptual understanding. From a common-sense engineering education perspective, it is clearly better to have a student who is able to solve problems with limited understanding that one who is not able even to attempt problems.

IMPLICATIONS FOR PRACTICE

Biggs[34] suggests that a key aspect of good teaching is "constructive alignment," where curriculum, teaching, and learning activities are all structured around the same objectives. What this study shows is that this is not a simple matter of design, due to the compounding influence of student perceptions. The course was "constructively aligned" in both design and execution, but one aspect of the course (time-pressured assessments) combined with another aspect of the broader program environment (high workload outside class) were overwhelming factors that led to a lack of necessary metacognitive development for a large proportion of the students. These aspects played out in ways that were not anticipated by the lecturers when they designed and taught the course.

Time-pressured assessments are frequently defended with the view that students will need to work fast in real-life situations. It may be argued that final-year assessments should to some extent simulate real-world pressures, but it is debatable whether such time-pressured assessment should be taking place during developmental stages of the program. The research findings of this study suggest that time pressure is manageable only if one is already comfortable with a conceptual approach. For students using a non-conceptual approach, time pressure is first of all unmanageable, but more importantly it inhibits experimentation with a new approach. Time-pressured assessments are not conducive to the risk taking that is a necessary part of metacognitive development. This thesis suggests that it is more important to support development toward a conceptual approach and that students will consequently be able to work fast, possibly with some practice in this area. Focusing on working fast without a conceptual approach is clearly disastrous, yet for a significant group of students this was their perception of the situation in this course.

The out-of-class workload was largely due to the other courses taken in parallel with this course that had a large number of hand-in assignments throughout the semester. Except for the journal assignments in the materials and energy balances course, the tasks that the lecturers required students to do outside class were not for marks. Therefore they took a lower priority than the hand-in assignments, and many students did not undertake the conceptual problems that the lecturers were hoping they would do outside class. One solution would have been to convert the tasks into hand-in assignments, but it is possible that this would only have exacerbated the situation. A more productive approach could be a coordinated approach to teaching and learning across the various courses. Not only is it arguable that the hand-in load should be reduced, but more importantly, a joint vision of the approaches to learning required and supported by all these courses would be highly beneficial. From students' descriptions of their approaches to learning, particularly in Mathematics II and Chemistry II, it seems that these courses were likely promoting algorithmic and information-based approaches to learning. Students would be more likely to adopt a conceptual approach if this was the message received in all their courses. This approach has been shown to be effective in secondary-school contexts.[35]

CONCLUSION

The first major finding of the study was that a conceptual approach was necessary and sufficient for success in this course. From the research literature and experience it would appear that this achievement is not to be underestimated, as there is ample evidence that students frequently manage to pass traditional assessment in tertiary science and engineering without necessarily understanding the work.[36]

The second, and more concerning, finding was that unless students were already using a conceptual approach at the start of the course, they were unlikely to make a change to it despite explicit attempts by the lecturers to foster development of such approaches. The major influence inhibiting this development appears to be the messages emanating from the highly time-pressured out-of-class and assessment environment. On one hand this finding seems to be obvious, and this paper is certainly not the first to suggest that time pressure can be detrimental to high quality learning.[1] On the other hand, however, any chemical engineering educator will at-

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Conceptual Understanding

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test to the longevity and power of the belief that students need to be able to perform assessments under time pressure and cope with a large volume of work outside class.

The research presented in this paper leads to fairly hard-hitting conclusions about engineering education practice. It suggests that reforming teaching to improve student learning is by no means a simple matter and that good intentions can easily be defeated by apparently minor aspects of the educational context. Most important, it has shown that designing a course that assesses for conceptual understanding and one that supports metacognitive development toward the use of a conceptual approach are *two* distinct ends. The former, although in itself challenging, is potentially easier to achieve, while the latter might require even more radical reform of taken-for-granted beliefs about the engineering curriculum. The assumption that students need to cope with large volumes of work and highly time-pressured ssessments would appear to work counter to the development of conceptual approaches and learning outcomes that include conceptual understanding.

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