

Conceptual gain in first-year chemistry: is the gap addressed effectively?

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7000 words

Context

Chemistry students enter tertiary institutions in South Africa with a wide range of proficiencies depending on the quality of instruction that they have received in school and many other factors. In a study that spans the last 8 years we have monitored the level of preparedness of chemistry students upon entry to university. Most South African universities offer academic development programmes for students who do not meet entry requirements to mainstream programmes. However, many students who are admitted to mainstream science programmes are also underprepared for the conceptual challenges awaiting them. The question arises to what extent do existing first year programmes achieve conceptual and skills development in order to address the deficiencies that students bring in from school.

Theoretical Framework

The underlying construct for this study is preparedness for tertiary chemistry. Preparedness in our view does not consist only of content knowledge, but also of conceptual understanding of fundamental concepts, assumed as pre-knowledge for tertiary chemistry. In addition, an appropriate level of mathematical and other skills, e.g. understanding of scientific terminology and representational competence, is required for mastery of chemistry at tertiary level. (Potgieter et al., 2008). We will also examine progress during the first year at university through this lens of conceptual gain in chemistry and the mastery of appropriate skills for doing and understanding chemistry.

Literature review

Most of general chemistry content, at the high school and university levels, is still taught and assessed in terms of facts, algorithms and procedural knowledge without emphasis on conceptual understanding (Hesse & Anderson, 1992, Nurrenberg & Pickering, 1987; Phelps, 1996). The instruction usually focuses on content breadth without a consistent emphasis on in-depth understanding and integration across concepts. It is often incorrectly assumed that students' procedural knowledge will translate into the development of conceptual understanding. (Nurrenberg & Pickering, 1987; Phelps; 1996, Sawrey, 1990). However, typical chemistry instructional organization does not promote conceptual understanding in most students (Hesse & Anderson, 1992; Bodner, 1991). During the past two decades a body of literature in science education has emerged focussing on teaching for conceptual understanding. For example, Gabel (1999) identified several effective strategies for learning in science which include the learning cycle approach, presenting science in context (STS) and real-life situations, using discrepant events and analogies, collaborative learning, wait-time, concept mapping and inquiry methods. A common thread in this work is that an emphasis on mathematical problem solving will result in the development of procedural skills, but not necessarily in conceptual understanding.

It has become widely accepted that traditional instruction is limited in its ability to achieve conceptual development in science education. Traditional instruction is loosely defined as that in which instructors "rely primarily on passive-student lectures, recipe labs, and algorithmic-problem exams" (Hake, 1998). A number of alternative pedagogies have been developed with the objective of improving conceptual gain and problem-solving abilities, such as cooperative learning (Springer et al., 1999), peer instruction (Crouch and Mazur, 2001) and just-in-time teaching (JiT) combined with peer instruction (PI) (Mazur & Watkins, accessed August 2010). What these methods have in common is the explicit objective to create opportunities for interactive engagement (IE) of students in class. IE methods are defined as those "designed at least in part to promote conceptual understanding through interactive engagement of students in heads-on (always) and hands-on (usually) activities which yield immediate feedback through discussion with peers and instructors" (Hake 1998). Most of the quantitative research in science education regarding the effectiveness of IE in a learning environment comes from the physics community, but it has been implemented in many scientific disciplines, including psychology and sociology.

It should be noted that tertiary chemistry educators and academics do not necessarily agree about what the learning outcomes of first-year chemistry must be, whether it should be a wide exposure to the myriad of topics in the discipline, problem solving skills (which is typically understood as procedural skills involving mathematical calculations) or conceptual understanding of fundamental chemistry processes and principles. While few would disagree that conceptual understanding is a prized outcome of science education and should be

one of the most important instructional goals of science teaching at both secondary and tertiary level one could argue that first-year students should also learn to do solve quantitative problem reliably and accurately and should have developed a basic appreciation for the scope of the discipline and its practical and scientific relevance. Perhaps it is safe to assume that first-year teaching and learning should achieve a combination of these outcomes which is carefully designed for balance and coherence, for in-depth understanding or shallow exposure where appropriate, and for appropriate skills development.

We have previously developed, tested and refined a diagnostic instrument for the assessment of preparedness for tertiary chemistry (Potgieter et al., 2008). This instrument, called the Chemical Competence Test (CCT), was specifically designed to assess conceptual understanding over a wide range of fundamental concepts which are typically assumed by tertiary lecturers to have been mastered before entry to university. We have also included several items in the instrument for the assessment of process skills development as stated earlier, but the explicit aim was to assess conceptual understanding rather than procedural skills with the majority of test items. The CCT instrument was used to establish entry level proficiencies produced by the former educational dispensation as well as the National Senior Certificate (NSC) and to document the shifts that occurred during the transition (Potgieter & Davidowitz, 2010). Learners who were taught according to the new syllabi contained in the NSC have a different profile of proficiencies than those who entered our universities before. Based on data collected with the CCT at three prominent South African universities in 2009 (UP, UCT and US; $N = 828, 315$ and 702 , respectively) we have recently described the best case scenario of the conceptual and skills profile of first-year chemistry students upon entry to tertiary studies (Potgieter & Davidowitz, unpublished results). The sample included only those students who completed the NSC in South African public schools in 2008, i.e. repeaters, international students and students from private schools were excluded. A total of 34 problem areas were identified where critical competences were lacking for more than 30% of students in these cohorts. This information can assist tertiary lecturers to structure their teaching in such a way that students are met where they are rather than where they are assumed to be.

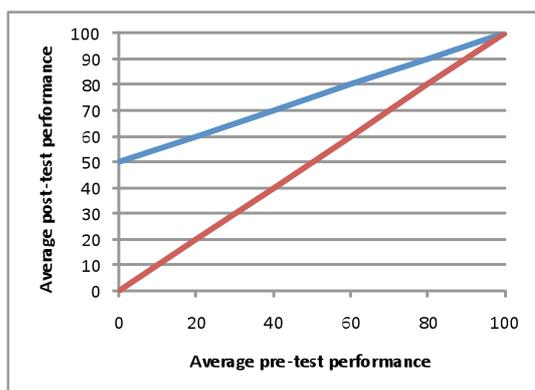
It may be argued that the CCT will not generate an accurate picture of what was achieved in the teaching and learning of chemistry during the first year at university. This instrument was designed to measure conceptual understanding at the foundational level, i.e. what lecturers often assume to have been mastered before entry to university this assumption has been shown to be inaccurate especially after introduction of the NSC (Potgieter & Davidowitz, 2010). If these deficiencies are not addressed effectively at first-year level students will struggle to grasp more advanced content resulting in the poor performance at first-year level that has been reported at almost all South African universities in 2009. While not measuring the full accomplishment of teaching and learning during the first year this instrument will nevertheless be very valuable in measuring the extent to which first-year teaching was successful in bridging the conceptual gap that exists between high school and university.

Methodology

In this paper we report on the use of the CCT to document gains in conceptual and skills development in first-year chemistry. The sample consists of seven different cohorts at five South African institutions, including three mainstream and four academic development cohorts. Data were collected between 2005 and 2010 by means of pre-tests and post-tests written by first-year students. The CCT instrument was administered as a pre-test at the start of instruction of a given year and again as a post-test close to the end of instruction before the final examinations. The test data provided information on entry and exit level performance on the CCT from which the conceptual gain achieved during the first academic year was calculated. The parameter used for this purpose, “average normalised gain”, $\langle g \rangle$, was defined by Hake (1998) for measuring conceptual gain in mechanics, Average normalised gain the ratio of the actual average gain $\langle G \rangle$ to the maximum possible average gain, $\% \langle G \rangle_{\max}$, i.e.

$$\langle g \rangle = \% \langle G \rangle / \% \langle G \rangle_{\max} = (\% \langle S_f \rangle - \% \langle S_i \rangle) / (100 - \% \langle S_i \rangle)$$

where $\langle S_f \rangle$ and $\langle S_i \rangle$ are the final (post) and initial (pre) class performance averages. Hake has argued that this parameter can be applied over a range of diverse student populations as a measure of the effectiveness of a specific course in promoting conceptual understanding because it corrects for the variation in entry level proficiencies that may exist between different samples. The implication of normalisation is demonstrated in Figure 1 where 0% (red) and 50% (blue) normalised gain is shown across the full spectrum of entry level performances, 0 – 100%.



Survey data was collected for all seven cohorts in our sample to describe them in terms of size, demographic composition as reflected by home language, the overall organisation of contact time, class size and the use and provision of study materials (Table 1). The organisation of contact time at the different institutions is loosely described in terms of lectures, tutorials and practical sessions. In this context a lecture refers to the formal presentation of disciplinary knowledge in a class setting, which may also include demonstrations of problem solving by the lecturer. Tutorials are generally small group problem solving sessions which require active student participation and are aimed at consolidation and application of theory taught in lectures. Practical sessions associated with mainstream courses typically involve recipe-based procedures for experiments which are not necessarily closely aligned with theory taught in lectures. Practical session in academic development programmes may be structured as a blend of practical work and problem solving activities.

Response frequency data from pre-tests and post-tests were analysed for evidence on gains achieved on 27 underdeveloped critical competences that are prerequisites for first-year chemistry. These results are reported in Table 2 and will be discussed below.

The differences in conceptual gain that were documented for the different cohorts in our sample will be the result of a multitude of factors of which we have started to investigate only a few. Learning gain can to some extent be ascribed to instructional practice which will be a reflection of lecturer conceptions about teaching and learning and the constraints within which teaching and learning must take place. In the second part of the study, which is still ongoing, an interview protocol was developed to capture data on elements of lecturer practice, instructional design, assessment, student engagement and learning support to interrogate underlying reasons for the differences in learning gain achieved in each of these settings. This interview protocol is based on the framework for articulating instructional practices and conceptions developed by Dancy and Henderson (2007) for introductory physics instruction at tertiary level. This framework was expanded to include details of assessment practices and learning support in order to provide a richer description of variations in the South African tertiary environment. Interviews have been conducted at three of the participating institutions and are being processed for subsequent analysis and interpretation. Interview data collection will continue during the rest of 2010. The results of this study will be presented anonymously to protect the identity of institutions and participant lecturers.

Sample

Seven different cohorts from five South African institutions were chosen as sample, including mainstream BSc as well as academic development cohorts. This was a convenience sample based on ease of access and collaboration between the author and chemistry lecturers at these institutions. These institutions are representative of the tertiary landscape of South Africa. They are located in four different provinces, and include both advantaged and historically disadvantaged institutions and represent different policies regarding the language of instruction. The institutions are labelled 1 to 5 to protect their identities and are described as follows:

Institution 1 is a historically black university serving predominantly rural communities. Two cohorts from this institution were involved in this study, i.e. the ADP cohort 1a in 2005 and the mainstream cohort 1b in 2007. The home language of ca. 95% of these students is one of the official African languages in South Africa and in general their entry level proficiencies were very low compared to that of the other cohorts (pre-test performance of 25% and 29%, respectively) (see Table 1). Institutions 2 to 5 are historically white universities which enjoy both national and international recognition. At institution 2 two cohorts of ADP students were involved in 2005 and 2007, respectively. These groups have a mixed demographic composition and consist of students who did not qualify for direct entry into the mainstream programmes. The fourth ADP cohort from institution 3 is again fairly homogeneous reflecting the fact that only students from disadvantaged backgrounds were admitted. As reported in Table 1 the entry level proficiencies of groups 2a, 2b and 3 were comparable and significantly higher than that of cohort 1a (pre-test performance 35 – 39% vs. 25%, respectively). The mainstream cohorts were also

almost homogeneous in composition with 94% English and Afrikaans speaking students at institutions 4 and 5 and 95% students with an African home language at institution 1. Cohorts 4 and 5 showed almost identical average pre-test performance when assessed in 2009 and 2010 which was significantly higher than that of cohort 1b (ca. 40% compared to 29%).

Results

Table 1 reports survey data for seven cohorts in terms of size, demographic composition as reflected by home language, the overall organisation of contact time, class size and the use and provision of study materials. The cohorts are further described in terms of entry and exit level performance on the CCT and average normalised learning gain. The ADP and the mainstream cohorts are grouped together and are listed in the order of increasing normalised conceptual gain, with highest gain demonstrated by cohorts 3 and 5 in their individual sections.

Table 1. Demographic and performance data for different cohorts of students at institutions 1 – 5.

		Academic Development cohorts				Mainstream cohorts		
Institution		1a	2a	2b	3	4	1b	5
Year		2005	2007	2005	2007	2010	2007	2009
Study Programmes						BSc, engineering and BPharm	BSc students eligible for chem major	Only BSc students
Home language [(A+E):African:Foreign]		03:96:01	24:73:03	31:65:04	04:94:04	94:06:00	04:95:01	94:05:01
Size of Cohort	Pre-Test	186	106	103	189	563	145	704
	Post-Test	175	78	98	181	486	158	620
No. of classes/groups		5	1	1	6	3	1	5
No of students per group		36	106	103	32	ca. 250	160 - 200	150 - 200
No of lecturers		2	1	1	3	2	1	4
Pass rate (%)		ca. 64	74	71	90	75	66	76
Average Performance (%)	Pre-Test	24.92	34.77	39.09	35.90	39.84	28.47	40.84
	Post-Test	30.12	45.99	52.43	51.07	41.95	34.09	48.08
Normalised gain (%)		6.9	17.2	21.9	23.7	3.5	7.9	12.2
Weekly contact time	Lecture	1	3	3	0	4	4	3
	Tut	2	2	2	4	0	0	4 of 14
	Prac (3h)	1	1	1	1	0.5	1	6 of 14
	Total time	300	350	350	300	290	350	320
Learning materials		Complete Workbook	Course notes filled in class	Course notes filled in class	Textbook, own class notes	Ppoint slides, tablet	Study guide outline, own notes	Ppoint slides, tablet

Reporting conceptual gain in terms of a single parameter masks a lot of finer detail about conceptual shifts that occurred in each cohort during the course of the first academic year. The prevalence of 27 conceptual problems and procedural deficiencies were obtained from response frequencies for items in pre-test and post-tests for each of the cohorts. This provided information about conceptual problems that seem to be easier to address, others that are fairly robust, and still others which seem to intensify rather than improve. The results of this analysis are reported in Table 2. Conceptual and procedural deficiencies are described in column 3 and are grouped under topics as shown in column 1 in the categories Basic concepts, Special topics and Process skills. Process skills include mathematical skills and representational competence, which is the ability to think and interpret at the three levels at which chemistry should be understood, i.e. macroscopic, submicroscopic and symbolic levels. The last five entries in the third column (32 – 35) describe procedural deficiencies specifically in terms of the ability of respondents to do mathematical operations required for calculations in chemistry.

Normalised conceptual gain is expressed for each of the problem areas as a ratio of the difference in prevalence of a specific problem in pre- and post-tests to the pre-test prevalence (the latter represents the maximum possible gain to be achieved). Negative values reflect conceptual gain whereas positive values reflect an increase in the prevalence of a specific problem. A maximum value of -100 indicates that a specific conceptual problem was eradicated. A positive value larger than 100 indicates that the prevalence of a specific conceptual problem has more than doubled in the post-test as compared to the pre-test. Conceptual gain was colour coded to indicate moderate gain (light green) and meaningful gain (dark green) or moderate deterioration of conceptual understanding (light red) and substantial growth of the prevalence of misconceptions (dark red). Fourteen items in our CCT instrument were obtained from an instrument developed by Mulford and Robinson (2002). They have also reported performance results for these items which we could use to calculate average normalised gain for comparison with our results (see values reported in column 4 of Table 2).