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TEACHING STUDENTS TO SELF-ASSESS THEIR KNOWLEDGE OF CHEMISTRY USING COGNITIVE STRUCTURE ANALYSIS

Ananya Dandemraju, Rithvik Dandemraju and John Leddo

MyEdMaster, LLC

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ABSTRACT

In previous papers, we presented an assessment methodology called Cognitive Structure Analysis (CSA) that assesses students' factual, strategic, procedural and rationale knowledge of a subject matter rather than looking at whether students can give the correct answer to a question. These results showed that CS-based assessments were highly reliable predictors of problem solving performance. In Cynkin and Leddo (2023), we explored whether students could be taught to use CSA to self-assess their own knowledge and, in doing so, identify gaps that might need remediation. The Cynkin and Leddo (2023) study showed that students could reliably by taught to self-assess their own calculus knowledge. The present study replicates this previous study and extends it to the subject of high school chemistry. 20 students were taught the chemistry topic of titration. After that, they were taught how to self-assess using CSA and then given a problem solving test. Results showed that students were generally reliable in self-assessing their own knowledge, recognizing when they knew a concept or did not know a concept that was important far more often than they did not realize they needed knowledge they did not have or having the wrong knowledge. Similarly, the self-assessed knowledge, or lack thereof, turned out to be important. The knowledge students correctly knew they had correlated .73 with problem solving performance, whereas knowledge students correctly knew they needed correlated -.44 with problem solving performance, suggesting that the lack of knowledge they knew they needed did hurt their performance. Self-assessments were not perfect as students did not always recognize gaps in their knowledge or that the concepts they had were faulty, both of which correlated negatively with performance, suggesting these deficiencies the self-assessed concepts did adversely affect their performance. Results suggest that students can be taught to self-assess their own knowledge. Further research can focus on whether students can self-remediate as well, and thereby raise their academic performance.

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

Introduction

Assessment has long been an integral part of the education process. It is seen as the measurement of how much students have learned the content that they were taught. In both classroom settings and in standardized testing, "learned the content" is typically operationally defined in terms of the number of correct answers a student gives on test questions. Indeed, classical test theory, one of the major pillars of assessment methodology, assumes that the total number of correctly-answered test items indicates the student's level of knowledge (cf., de Ayala, 2009).

Over the years, a number of assessment frameworks have been utilized by teachers and educational organizations. Typically, these can be categorized by whether students are asked to select the correct answer from a set of answer choices or asked to construct their own answers to problems. There has been considerable debate over which category of method is better, with pros and cons attached to each. Multiple choice tests require students to select answers from several distractors. Multiple choice tests are widely used in standardized testing and in many classroom settings due to the ease of grading (Chaoui, 2011) and the fact that students often score higher on multiple choice tests than they do on constructive response tests as students can increase their scores through guessing (cf. Elbrink and Waits, 1970; O'Neil and Brown, 1997). However, such guessing is often cited by critics as a reason why multiple choice tests should not be used.

At the other end of the continuum are constructive tests, which require that students enter answers to questions rather than choose from different answer choices. Researchers find, when investigating math problem solving, that students are more likely to use guessing strategies when given multiple choice tests but are more likely to reason mathematically when given constructive tests (Herman et al., 1994), thus making the test more ecologically valid in measuring students' actual knowledge (Frary, 1985).

The challenge with the key assumption of classical test theory, that correct answers indicate learning and vice versa, is that this assumption may not be entirely true. A medical analogy works well here. Normally, if a person shows outward signs of illness, s/he is probably sick (although there could be non-medical reasons why a person can appear sick such as overexertion or lack of sleep). Similarly, a student who makes a lot of mistakes on a test probably has a lack of knowledge (unless, for example, s/he was distracted or sick during the test). However, a person can look healthy and still have an underlying illness. Similarly, a student may get correct answers on a test and have knowledge deficiencies. They can be parroting facts or formulas that they do not really understand or guessing correctly on multiple choice exams (which is a major criticism of that testing format).

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

More importantly, the lack of correct answers does not inform the teacher as to what concepts need to be remediated. A doctor does not stop his/her diagnosis after observing symptoms. The doctor runs further tests to discover the cause of the symptoms, so that an appropriate remedy can be applied. Indeed, we would consider it medical malpractice for a doctor to treat only the symptoms and not the underlying causes of diseases. Similarly, an incorrect answer to a test question is a symptom that may indicate an underlying knowledge deficiency. We consider it to be educational malpractice to stop the assessment at that point without diagnosing the underlying knowledge deficiency that is causing that incorrect answer. Unless that cause is identified, how can the appropriate remedial instruction be given?

Previously, we have reported an assessment methodology called Cognitive Structure Analysis (CSA) that is designed to assess the underlying concepts a student has, so that when a student does make a mistake, the source of that mistake can be identified and remediated (Leddo et al., 2022; Ahmad and Leddo, 2023; Zhou and Leddo, 2023). CSA is based on decades of cognitive psychology research that have shown that people possess a variety of knowledge types, each of which is organized and used differently in problem solving. Because there are different types of knowledge that people have, our framework is an integration of several prominent and well-researched formalisms. These include: semantic nets, which organize factual information (Quillian, 1966); production rules, which organize concrete procedures (Newell and Simon, 1972); scripts, which are general goal-based problem solving strategies (Schank and Abelson, 1977; Schank, 1982); and mental models, which explain the causal principle behind concepts (de Kleer and Brown, 1981). Because our framework integrates these four knowledge types, it is called INKS for INtegrated Knowledge Structure.

The INKS framework is based on research by John Leddo (Leddo et al., 1990) that shows that true expertise in a subject area requires all four knowledge types. INKS also has implications for instruction. For example, in John Anderson's ACT-R framework, people initially learn factual/semantic knowledge that is later operationalized into procedures (Anderson, 1982). Research by Leddo takes this one step further showing that expert knowledge is organized around goals and plans (referred to in the literature as "scripts" – Schank and Abelson, 1977; Schank, 1982) and abstracted into causal principles (referred to in the literature as "mental models" – cf., de Kleer and Brown, 1981) that allow people to construct explanations and make predictions/innovations in novel situations.

In order to identify the root cause of the mistake, we use a query-based assessment framework called Cognitive Structure Analysis (CSA, Leddo et al., 1990). CSA incorporates principles from the INKS knowledge representation framework. In our recent research, assessments produced by CSA correlated .966 with problem solving performance in Algebra 1 (Leddo et al, 2022), .63

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

with problem solving performance in the scientific method (Ahmad and Leddo, 2023), and .80 with problem solving performance in pre-calculus (Zhou and Leddo, 2023).

As argued above, the value of CSA as an assessment tool is that it can provide teachers with a means of assessing what concepts students have and are lacking, so that appropriate remedial instruction can be provided. However, this line of reasoning presupposes that a teacher is the one who does the assessment and remediation. In a previous paper (Cynkin and Leddo, 2023), we explored whether high school students taking calculus could be taught to self-assess their own knowledge using CSA and in doing so, potentially identify gaps in their knowledge that might be responsible for mistakes that they make or times when they feel stuck when solving problems. Cynkin and Leddo found that students could be taught to assess their knowledge quite accurately. The present paper seeks to extend these findings to another subject area: high school chemistry.

Methods

Participants

There were 20 male and female high school participants with previous chemistry knowledge, 10 having taken AP chemistry and the other 10 took regular chemistry. We chose students who had at least some prior chemistry knowledge. On the lower end, they had taken and completed Academic Chemistry; on the more advanced side, others had taken AP Chemistry. This varying knowledge range ensured the present experiment had students with a range of chemistry expertise,

Materials

Before doing the self-assessment, participants were asked to watch two videos. One video was about the titration process, and the other was about the math involved when solving titration problems:

Math: https://youtube.com/watch?v=ovx-Sro4NXM&feature=share

Process: https://youtube.com/watch?v=YqfvRBJ-iPg&feature=share

The participants were also given a sample script that they could use to train them on how to self-assess. The script illustrated a self-assessment for solving equations in Algebra 1. The script is shown below..

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

Script for Self Assessment

"For facts, I need to know what variables, constants, coefficients, equations, and expressions are. A variable is an unknown quantity, usually represented by a letter. A constant is a specific number. A coefficient is a number you multiply a variable by, like 2x. An equation is an expression equal to another, and an equal sign joins the two expressions. An expression is one or more terms combined by mathematical operations like addition, subtraction, multiplication, and division.

For strategies, I need to know the reverse order of operations, SADMEP. This means subtraction, addition, division, multiplication, exponents, and parentheses. I know I'm supposed to do these in order, but I don't remember whether I'm supposed to always do subtraction before addition or just which one goes first. The same is valid for division and Multiplication.

For procedures, I need to know additive inverse and multiplicative inverse. The additive inverse takes the number with the opposite sign as the constant and adds it to both sides of the equation. The multiplicative inverse is taking the inverse of the coefficient of the variable and multiplying both sides of the equation by it. However, if the coefficient is negative, I'm not sure if the multiplicative inverse is supposed to be negative as well.

For rationales, the two rationales I need are the subtraction property of equality and the division property of equality. The subtraction property of equality says that if I subtract the same number from both sides, which I'm doing with the additive inverse, I preserve the equality. Similarly, the division property of equality says that if I divide both sides of the equation by the same number, which I'm doing with the multiplicative inverse, I preserve equality.

When I look over what I wrote, I see that I am good with my facts. On my strategy, I'm unsure about the order of steps in reverse order of operations when it comes to subtraction, addition, multiplication, and division, so I need to learn those. On procedures, I'm not sure what to do with multiplicative inverses when the coefficient is negative, so I need to learn that as well. For rationale, I think I'm OK. I don't think I have any missing facts/concepts that I left out that I should know or I didn't list any facts/concepts where I didn't know what they were. For the strategy, I believe I listed the correct strategy and parts of the strategy, but I wasn't sure about some of the ordering of steps in the strategy. For procedures, I was good on the additive inverse but had a question on carrying out the multiplicative inverse when the coefficient was negative. For rationales, I think I had all the rationales that were important and that I understood them as well. I don't think I left anything out."

The assessment given to participants to display their knowledge is linked below.

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

https://forms.gle/taMKHz4QnbGEJQVn6

Procedure

After Participants watched both videos, they performed the self assessment. Participants were given the self assessment script and were then asked to create a similar self-assessment based on their understanding of the topic contained in the videos they just watched. Participants wrote their self-assessments on Google Forms. In the self assessment they were assigned to write about the knowledge they had in the four categories: facts, procedures, strategy, and rationale. After they finished the self assessment, they were given a post-test on the same Google Form, so that the self-assessments would be directly linked to the answers given to the problems. The post-test consisted of five fact questions, two questions on procedure, three questions on strategy, four rationale questions, and 4 problem solving questions.

Results

Analysis of the Participants' data consisted of evaluating the number of correct answers on the post-test and evaluating the accuracy of the self-assessments. Analysis of the post-test responses showed a range of scores with an average post-test score of 10.75 out of 18.

For the self-assessment portion, each piece of knowledge listed by the Participants was assigned to one of the following scoring categories: correct knowledge, incorrect knowledge, false alarm knowledge, missed knowledge, know that they don't know, and think they don't know but irrelevant. The "correct knowledge" category was knowledge that students believed they needed to know, did need to know and did have accurate knowledge. The "incorrect knowledge" category was knowledge that students believed they needed to know and did need to know but had incorrect knowledge. The "false alarm knowledge" category was knowledge that students believed they needed to know, did have the knowledge, but the knowledge was not relevant to the topic. The "missed knowledge" category was knowledge that students needed to know but did not mention. The "know that they don't know" category was knowledge that students knew that they needed to know, did need to know and knew that they did not have this necessary knowledge. Finally, the "think don't know but irrelevant" category was knowledge students thought they needed to know, knew that they did not have the knowledge, but the knowledge was actually unnecessary to understand the subject.. The averages number of items that fell into each category is shown below along with the average post-test score:

What is of particular interest in the data is that students were generally pretty good at assessing their knowledge strengths and weaknesses. Within the above table, the "correct knowledge" and "know they don't know" cells represent cases where students have identified the important concepts they should have to solve the problems. False alarm knowledge (believing something

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

was important when it was not) and "think they don't know but irrelevant" are the two categories in which students believed knowledge was important that really was not and the sum of the averages in these two columns is close to 0. On the other hand, genuine errors in the self-assessment (having incorrect knowledge or not realizing that knowledge is important ("missed knowledge") did occur. However, the average instances of these two types of errors (7.1) was much lower than the average instances of the two correct self-assessment category items (12.9), t (paired) =6.09704, df = 19, $p < .01$.

correct knowledge:	incorrect knowledge:	false Alarm knowledge:	missed knowledge:	know that they don't know:	think don't know but irrelevant:	Post-test score
12.2	3.5	0.4	3.6	0.7	0	10.75

The high correlation coefficient (r= 0.73, p< .0005) between correct knowledge and overall score is one striking discovery, demonstrating a significant positive association. This means that students who displayed a strong understanding of facts, methods, strategy, and rationale performed well on the knowledge quiz overall. In contrast, there was a strong negative association (r = -0.50, p< .05) between inaccurate knowledge and overall score, indicating that misconceptions or errors in comprehension were related with lower exam scores.

Other correlations were also instructive. The correlation for missed knowledge (r = -0.59, p <.01) showed that when students did not realize that key concepts were important, their performance suffered. A similar finding occurred for knowledge students knew they needed by did not have (r = -.44, p = .05). On the other hand, false alarm knowledge (knowledge that was ultimately irrelevant to performance) did not correlate significantly with performance (r = .28, ns).

Discussion

The study aimed to assess whether students could accurately self-assess their own chemistry knowledge. Overall, students were generally able to self-assess concepts that they correctly knew and were missing in their knowledge. Moreover, results show that the knowledge students thought was important to know and did know correlated highly with their problem solving performance and knowledge that they knew that they were lacking and showed a negative correlation. This creates an opportunity for students to improve their own performance by seeking remedial instruction in those areas.

ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

There are additional research questions that remain regarding training students to self-assess. One is that our previous work and the present study focused on high school students. The question is whether younger students can also be taught to self-assess reliably. Perhaps even more importantly, once a student has completed a self-assessment, can that student do self-remediation as well? Will the student be able to gauge reliably when s/he has corrected the knowledge deficiencies and will this self-remediation lead to higher performance?

However the answers to these questions play out, it seems clear that the idea of teaching students to self-assess and self-remediate can play an important role in the educational process. Since teachers tend to have more students than they can reasonably teach on a personalized basis and given the cost of private tutors (who could also assess and remediate students on an individual basis) is prohibitive as a scalable solution across education, self-assessment and remediation offers a possible way to help those students who get stuck while learning and are unsure how to “unstick” themselves.

Looking ahead, these findings could inform the development of adaptive assessment strategies that cater to individual learning styles and address specific knowledge gaps. By integrating self-awareness into the assessment process, educators may be better equipped to tailor interventions and support students in areas where they need it most, ultimately contributing to more effective and personalized educational practices.

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ISSN: 2455-8834

Volume:09, Issue:02 "February 2024"

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