

A Closer Look at the Relationships between College Students' Cognitive Abilities and Problem Solving in Stoichiometry

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Abstract

Several cognitive abilities were investigated in order to determine whether they correlated with undergraduates' ability to solve stoichiometry problems. The problems were analyzed and broken down into constituent sub-problems in stoichiometry. Students were given a series of tests to measure their cognitive abilities in working memory capacity, formal reasoning, cognitive development, and conceptual understanding of the particulate nature of matter and the mole concept. A mixed qualitative and quantitative approach was used to analyze students' difficulties with stoichiometry problems. The investigation of the cognitive variables indicated that only formal reasoning ability and understanding of the mole concept were good predictors of students' success in stoichiometry. Although understanding of the particulate nature of matter did not correlate with success in solving general stoichiometry problems, it was significantly correlated with writing and balancing chemical equations.

Keywords: Cognitive Variables, General Chemistry, Problem Solving, Stoichiometry

Introduction

Stoichiometry and Cognitive Variables

The more students' abilities at solving problems are investigated, the more it is understood that problem solving is a very complicated and challenging task, especially in chemistry (Bird, 2010). Stoichiometry, one of the many complex topics in chemistry, requires a series of skills, organized knowledge of chemistry, and mathematical ability. Successful problem solving in stoichiometry requires the solver to calculate molecular weight, understand the mole concept and the particulate nature of matter, balance chemical equations to find the correct stoichiometric ratios, determine the limiting reagent, and more. As a result, many students view this aspect of chemistry as one of the most difficult (Astudillo & Niaz, 1996; Schmidt, 1997; Stieff & Wilensky, 2002), which can discourage them and cause them to lose their self-confidence, which research has shown is important for success (Ajzen, 2002; Bauer, 2005; Bowman, 2012).

Although some students have the knowledge of chemistry and mathematical abilities to solve simple problems, they cannot use and link their knowledge of different topics to carry out complex calculations. It seems that their knowledge is composed of isolated facts and separated through different domains. It is widely accepted that students' performance during

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problem solving is affected by students' knowledge structures (Bédard & Chi, 1992; Chi, Glaser & Rees, 1981; Gerace, 2001). Students who do not have conceptually organized knowledge have difficulties in solving problems. It is also known that students' problem solving performances are influenced by not only their knowledge structure but also various cognitive variables (Bauer, 2005, 2008).

There are different types of cognitive variables. Some are related to students' prior knowledge and some related to students' capacities, abilities, and skills. Although it would be ideal to include as many cognitive variables as are mentioned in the literature as factors in problem solving, limited time and resources prevent that possibility. It is important to consider as many variables as possible in order to better understand the complex process of problem solving (Lyle & Robinson, 2001; Ross & Fulton, 1994). Table 1 shows a list of some of the potential cognitive variables that may affect a student's ability to solve a stoichiometry problem.

Table 1. Some cognitive variables that may affect a student's ability to perform stoichiometry problems

Cognitive development	Huitt and Hummel (2003)
Formal (proportional) reasoning	Kwon, Lawson, Chung, and Kim (2000)
Working memory capacity	Miller (1956), Stamovlasis and Tsaparlis (2000), Baddeley (2002)
Conceptual understanding of mole concept	Nakhleh and Mitchell (1993), Phelps (1996)
Conceptual understanding of particulate nature of matter	BouJaoude and Barakat (2003), Cui, Zollman, and Rebello (2005)
Probabilistic reasoning	Bird (2010)

The Effects of Cognitive Development and Proportional Reasoning on Problem Solving

Piaget claims that intellectual and mental development take place in four periods, which have great effect in people's ability to learn. Development begins at the sensorimotor stage in infancy, proceeds through the pre-operational stage in early childhood, to the concrete operational stage in early adolescence, followed by the mature stage of formal operation (Cantu & Herron, 1978; Huitt & Hummel, 2003; Piaget, 1950). In the concrete operational stage, manipulation of symbols related to concrete objects is observed, while in the formal operational stage, intelligence is associated with the use of symbols related to abstract concepts. According to Huitt & Hummel, "only 35% of high school graduates in industrialized countries obtain formal operations; many people do not think formally during adulthood," which has been confirmed by other researchers (Bird, 2010).

Advancement to the fourth stage of cognitive development is necessary for students to succeed with stoichiometry (Niaz & Robinson, 1992). Chemistry as a whole is mostly abstract to students, and stoichiometry is one of those abstract topics in chemistry (Childs & Sheehan, 2009). If students do not complete their cognitive development to the formal operational stage, they may not be able to deal with abstract topics; if students are not ready to deal with abstract and complex structures when they come to the classroom to learn stoichiometric concepts, they may have hard time in understanding them and may fail in solving stoichiometric problems. Atwater and Alick (1990) investigated the level of cognitive development of African-American students enrolled in general chemistry courses to determine the strategies used by both successful and unsuccessful problem solvers in solving stoichiometry problems. Results indicated that a higher level of cognitive development might be crucial in solving the problems that are more sophisticated.

In addition to Piaget's cognitive development measures, proportional reasoning, a person's ability to effectively see the relations and ratios between quantitative variables, plays a central role in solving stoichiometric problems as well. Lesh, Post, and Behr (1988) define proportional reasoning and explain its relation with processing information to reach solutions as follows:

“Proportional reasoning is a form of mathematical reasoning that involves a sense of co-variation and multiple comparisons, and the ability to mentally store and process several pieces of information. Proportional reasoning is very much concerned with inference and prediction and involves both qualitative and quantitative methods of thought.”

According to Inhelder and Piaget (1964), the proportional reasoning ability is a major component of the individual's mind, which has completed its cognitive development and it is now at the formal operational stage. The proportional reasoning ability helps individuals solve problems involving ratios in mathematics, which also leads to success in chemistry (Bauer, 2005).

Figure 1 indicates a common pattern for stoichiometric calculations. Students must use proportional reasoning abilities to go from the number of moles of the substance A to number of moles of substance B. However, experimental evidence has shown that a significant number of college freshmen are not good at using proportional reasoning abilities (Bird, 2010; McKinnon & Renner, 1971; Ward, Nurrenbern, Lucas, & Herron, 1981).

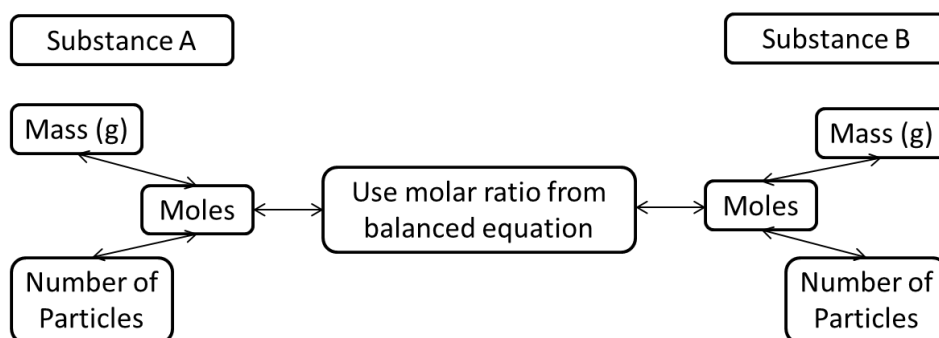


Figure 1. A flow chart for solving stoichiometry problems

In the literature, proportional reasoning is shown as one of the vital requirements in problem solving in science and other contexts (Kwon et al., 2000). The significant relationship between students' proportional reasoning abilities and their success in solving problems has been observed in several studies (Akutugba & Wallace, 1999; Bird, 2010).

Working Memory Capacity

In the 1950's, debate about the function and the description of short-term (working) memory increased in the field of information processing (Baddeley, 1986). Whether one viewed short-term and long term memory as components of one large system (Baddeley, 2002), or two separate systems (Kintsch, 1970), working memory played an essential role in manipulating information and performing the complex cognitive tasks such as learning and reasoning (Baddeley, 1986). Miller (1956) and Shiffrin and Nosofsky (1994) discovered that the size of working memory is limited; in other words, working memory has a finite capacity.

Johnstone and El-Banna (1986) explored the relationship between working memory capacity and success in chemistry. They claimed that working-memory capacity was a good

predictor of student performance in problem solving in chemistry (Johnstone, 1984; Johnstone & El-Banna, 1986, 1989). Data from both secondary and tertiary education were shown to be in general agreement with their hypothesis, but the authors admitted that working memory capacity was not the only factor affecting students' performances.

Furthermore, Opdenacker et al. (1990) investigated the correlation between working memory capacity and problem solving performance, as hypothesized by Johnstone and El-Banna (1986), using two hundred and fifty undergraduate medical students. The digits backwards test (DBT) and the figural intersection test (FIT) were used to assess the working memory capacity of students. They found a moderate correlation between the size of working memory and problem-solving ability, and also determined that working memory capacity was only one factor affecting problem solving ability.

Conceptual Understanding and Problem Solving

Johnstone and Kellett (1980) believed that developing conceptual understanding (knowledge) influenced the students' success in solving problems, and that being fluent and flexible in recalling relevant information would increase the chance of being successful in solving problems. Conceptual understanding, then, is believed to be the most important factor in problem solving success (Bédard & Chi, 1992). Experts' achievement in the recognition of patterns and interpreting different aspects of problems that can lead to successful solutions can also be accounted for by their better conceptual understanding of subject matter (Phelps, 1996). Conceptual understanding in stoichiometry has been shown to be important in student success, as well (Arasasingham, Taagepera, Potter, & Lonjers, 2004; BouJaoude & Barakat, 2003; Gauchon & Meheut, 2007). Recent studies also show that failure in the understanding of chemical concepts such as the mole concept (i.e., chemicals react in fixed mole ratios as defined by a chemical equation) and chemical reactions results in misunderstandings in chemistry (Dori & Hameiri, 2003; Gabel & Bunce, 1994).

This does not mean, however, that conceptual understanding guarantees correct solutions. It has been observed that a few students have difficulty formulating algorithms for problems even though they have conceptual understanding of the subject (Nakhleh & Mitchell, 1993). Likewise, students who can solve problems algorithmically do not necessarily have a conceptual understanding of the problem (Nurrenbern & Pickering, 1987). This illustrates the importance of having a combination of skills including procedural knowledge, which is required for successful problem solving. For problems that are not purely algorithmic in nature, it is important to have the right combination of skills to unlock the problem and solve it.

Developing a good conceptual understanding of stoichiometry is closely associated with the belief that matter is made of particles not visible to the unaided eye, that changes observed at the macroscopic level can be explained in microscopic terms, and that these concepts can be represented by symbols (Gabel & Bunce, 1994). Williamson, Huffman, and Peck (2004) have suggested that understanding the particle model will provide the learner with many benefits, such as a better comprehension of chemical concepts and more effective problem solving skills (Harrison & Treagust, 2002; Tuncer, 2003; Valanides, 2000). Lacking conceptual understanding of the particulate nature of matter could cause difficulties in learning subsequent chemistry topics and encourage dependence on previously memorized techniques. Studies indicate that the stoichiometric relationship between atoms, molecules, and reactants and products are not recognized well (Dori & Hameiri, 2003).

It can clearly be seen that there are many challenges and difficulties in learning chemistry and, in particular, the particulate nature of matter. The difficulty in understanding the particulate nature of matter brings difficulties in understanding and representing changes

at the macro, micro, and symbolic levels and makes problem solving in chemistry difficult. Understanding how student success correlates with conceptual understanding and other cognitive variables is important for the continued development of effective teaching techniques in stoichiometry.

Methodology

Research Question

In this research project several cognitive abilities were investigated in order to determine whether or not they correlated with ability to succeed in solving stoichiometry problems and aimed to answer the research question, “What are the roles of cognitive development, proportional reasoning abilities, working memory capacities and conceptual understanding of particle nature of matter and mole concept in problem solving success in stoichiometry?”

Stoichiometry and Its Sub-Problems: A Challenging Topic and Its Constituents

The study aimed to examine the influence of cognitive variables on students’ problem solving performances in stoichiometry, which is one of the most problematic topics for general chemistry students (Felder, 1990). In order to better illuminate the roles of cognitive factors, solutions of problems associated with sub-problems within stoichiometry were closely examined, rather than looking at stoichiometry as a one whole topic. These sub-topics can be seen in Table 2; they were chosen as they were the most common sub-problems present in the stoichiometry problems used.

Table 2. Abbreviations for stoichiometry sub-problems

Stoichiometry sub-problem	Abbreviation
Writing chemical equations	WEQ
Balancing chemical equations	BEQ
Mass percent	MP
Percent yield	PY
Empirical formula	EF
Molecular formula	MF
Limiting reagent	LR
Mole concept	MC
Stoichiometric ratio	SR

Participants

Eighteen science majors participated in the study at a Midwestern university in the United States of America; one student was excluded from the study because they were unable to complete all four think-aloud sessions, which brought the final total to 17. The study took place in a spring semester while all students were taking General Chemistry II. One of the authors was the instructor of the General Chemistry I course and knew all the students but was not teaching while the study was carried out. Students volunteered and gave their informed consent to participate in the study, and each student that participated was paid a stipend for each session attended. Volunteers were given a chemistry aptitude test to determine their chemistry ability prior to beginning the study; the nine highest and lowest scoring students of a larger initial volunteer pool were chosen to be participants in the study.

Design

For this study, a mixed-method approach was employed, using “think-aloud” protocols and several tests to measure cognitive variables that had already been validated for use (Table 3). The tests constituted the quantitative part of the research and think-aloud protocols the qualitative part of the research, which was later, converted into quantitative figures in order to run statistical tests. The combination of these two approaches yielded correlations between different variables in problem solving and a better understanding of the challenges that students face in the problem solving process.

The cognitive variable tests (Table 3) were administered to all seventeen students in the study over the course of two days. The tests were administered at the same time for all students; the TOLT and BPCI were administered on one day and the LT and MC-AT were given the second day. All tests were given in a paper and pencil format.

Table 3. List of cognitive variable tests used

Test	Abbreviation	Cognitive variable measured
Test of Logical Thinking	TOLT	Formal (proportional) reasoning
Longeot Test	LT	Cognitive development
Digits Backwards Test	DBT	Working memory capacity
Berlin Particle Concept Inventory	BPCI	Understanding of particulate nature of matter
Mole Concept Achievement Test	MC-AT	Conceptual understanding of mole concept

Think-Aloud Protocol

The think-aloud sessions were scheduled for a total of four different appointments on four different days for each student. The think-aloud protocols were taken over the course of two months. To determine students’ working memory capacities, the DBT was given on first day of the think-aloud protocol, which took about twenty minutes. The remainder of the think-aloud protocol involved having students solve problems while voicing out-loud their thought process as they proceeded. Some directed questions were asked by the protocol administrator to clarify students’ thoughts at the time. Both audio and video recordings were made during the sessions. The video recordings were primarily used to clarify statements made by students when referring to their work.

Students completed a series of four think-aloud sessions. Each of the problems analyzed in the think-aloud protocol was comprised of at least two sub-problems, with as many as five different sub-problem types (some sub-problems showed up multiple times in each problem). The first session involved, as mentioned above, the DBT, and two or three stoichiometry problems. The students who only solved two problems in the first session had extended second sessions to compensate.

In the second session, students attempted to solve twelve questions about the writing and balancing of reactions, percent composition, empirical and molecular formulae, percent yield, and the mole concept. In the third session, students solved seven stoichiometric questions with similar subject matter to the second session; problems in the third session were more difficult than those of the second session. Finally, in the last session, students completed the think-aloud protocols by solving five more complex stoichiometric questions, which evaluated their problem solving performance in stoichiometry.

After the think-aloud sessions were complete, the transcripts from the audio recordings collected during the sessions were analyzed. For each of the sub-problems (Table 2) in each of the stoichiometry problems that a student performed, their performance on paper was

categorized using audio and video cues into one of three categories: successful, neutral, or unsuccessful. If a stoichiometry problem had four sub-problems (i.e., steps), one code would be assigned to each of the four sub-problems, for a total of four different codes. A successful code was only assigned if the sub-problem was done correctly and without assistance. A student's attempt on a sub-problem was classified as neutral when the student either did not know that the sub-problem was necessary or was able to skip the sub-problem by using a different method of calculation. These are considered "neutral" because a student may know how to calculate the expected sub-problem, but no evidence for that exists because they did not do the sub-problem. Unsuccessful sub-problems were those for which students needed hints or performed the sub-problem incorrectly.

These qualitative observations of students' stoichiometry-solving procedure were, thus, converted into quantitative values by tallying the occurrence of each of the major categories, tallying the sub-divisions in each category (not discussed in this paper), and calculating the attempt success rate (ASR) for each sub-problem. ASR was calculated as the number of successful attempts on a specific sub-problem divided by the sum of the successful and unsuccessful attempts on that sub-problem. Neutral classifications were excluded from the ASR calculation as the goal was to measure success only when students attempted a sub-problem. This is different from the total success rate (TSR) described below. The ASR was considered, as a variable, to be sufficiently continuous so as to be usable in correlation calculations. The coding system used a total of eight codes (1 successful, 3 neutral, and 4 unsuccessful codes) for complete classification. Though they were condensed for this study, further information, especially on what constituted successful, unsuccessful, or neutral, can be seen in Gulacar and Fynewever (2010).

Quantitative Test Descriptions

TOLT

The first test subjects took was the Test of Logical Thinking (TOLT) (Tingle & Good, 1990; Tobin & Capie, 1981). The TOLT is a paper and pencil instrument, which evaluates logical thinking. It measures proportional reasoning, control of variables, probabilistic reasoning, correlational reasoning, and combinatorial reasoning. Although, in the original version, the test was scored on a scale of ten, for statistical purposes a scale of 100 was used in this study.

The TOLT has been used with students in several grades from middle school to college. The reliability of this test ranges from .80 to .85, as measured by Cronbach's α (Tobin & Capie, 1981). The TOLT has been shown to be a good predictor of chemistry achievement (Sanchez & Betkouski, 1986). The reliability of the TOLT, as used in this study, was $\alpha = .58$ for the overall TOLT and $\alpha = .82$ for the proportional reasoning portion questions.

BPCI

The second test in the study was the Berlin Particle Concept Inventory (BPCI), which measured students' grasp of the particulate nature of matter. The BPCI was developed by Milkelskis-Seifert in Germany and translated into English by a group of researchers at Kansas State University (Cui et al., 2005); the test is available from the authors. The BPCI contains 70 statements, each of which are rated on a four-point Likert Scale from true to false. Respondents also rate themselves as being either certain or uncertain of each answer. A Likert scale was used because, for most of the questions, the correct answer for a novice may be incorrect for an expert, and even the experts may disagree based on their level of expertise. For example, it might be difficult to have consensus on the following statement: "Since particles exist, sooner or later their size and shape will be determined exactly." (Cui et al.,

2005). Moreover, Likert scale questions allowed for the study of the vagueness of student choices, which might better represent their mental models.

In the BPCI, the questions were categorized into eight categories as suggested by Cui et al. (2005): (1) Existence of particles and their experimental evidence, (2) relationship between characteristics of the individual particles and characteristics of the object they form, (3) material (air or vacuum) between the particles, (4) density, volume, mass, weight, and their relationship, (5) forces between particles, (6) difference between solid, liquid, and gaseous state, (7) relationship between shape, mass, and volume of the individual particles, (8) relationship between temperature and particle properties. The inter-rater reliability (Cohen's kappa) of the categories was 82% (Cui et al., 2005).

Longeot Test

The third test in the study was the Longeot Test (LT) (Sheehan, 1970). The LT, originally published in French, was designed to measure various aspects of formal thinking. Its twenty-eight items are divided into four parts. The first part contains five items involving the concept of class inclusion. The second part of the test has six items of propositional logic, the third part consists of nine items designed to measure proportional reasoning, and the fourth part of the test consists of eight combinatorial analysis problems requiring subjects to list all possible combinations of a set of items. Validity and reliability of the English version of the Longeot test had been studied by earlier investigators (Pandey, Bhattacharya & Rai, 1993; Sheehan, 1970; Ward et al., 1981). Sheehan's results (1970) indicated that the test was effective in differentiating between concrete and formal thinkers. Ward et al. (1981) claimed the test to be reliable as the internal consistency ranged from .72 to .78 (Cronbach's α) over a wide range of class types.

Gabel and Sherwood (1979) used the LT to study high school students. Their study was designed to see if there was any interaction between students' developmental levels and their ACS (American Chemical Society) and NSTA (National Science Teachers Association) chemistry achievement exam scores. Although they did not run a detailed statistical analysis, the comparison of the students' cognitive development level and their ACS scores revealed that the students at the formal operational level had better scores. In this study, as in Ward et al.'s study (1981), the LT was used to measure the cognitive development of undergraduates. The goal in this study was to determine if there was a correlation between college students' cognitive development and their success on stoichiometric problem solving. The original scoring rubric rates students on a scale of 0 – 42. For the purposes of this paper, the rubric was converted into a percentage scale, with the original 42 becoming 100%.

MC-AT

The fourth test in the study was the Mole Concept Achievement Test (MC-AT) (Yalçinalp, Geban, & Özkan, 1995). This test was developed by various researchers to identify students' conceptual understanding of the mole concept, the meaning of subscripts in chemical formulas, and the mathematical application thereof (Gower, 1977; Griffiths, Kass, & Cornish, 1983).

Content validity of the test items was established by a group of experts in chemistry and science education. The reliability coefficient was estimated to be .88 (Cronbach's α) (Yalçinalp et al., 1995). Previous researchers mostly employed the MC-AT to examine the students' understanding of the mole concept but this test was used to determine the influence of the conceptual understanding of the mole concept on students' problem solving performance in stoichiometry.

DBT

The final test used in this study was the Digits Backwards Test (DBT) (Johnstone & El-Banna, 1986; Opdenacker et al., 1990). The DBT consists of reading a set of digits to the subjects and asking them to repeat them in writing in reverse order (i.e., 3245 would return 5423). In the DBT, subjects were asked to repeat an arbitrary sequence of digits, steadily increasing in size, in reverse order. The quantity of working memory capacity, X , was defined as an integer corresponding to the maximum number of digits that could be repeated in reverse order without mistakes at least 50% of the time (Opdenacker et al., 1990).

TSR

The final piece of quantitative data was collected from the solutions generated by the students during the think-aloud protocols. Unlike the ASR described above, the total success rate (TSR) was calculated using successful, unsuccessful, and neutral codes. The only code not included in the TSR was the “not required” code, since the code indicated a student had skipped the sub-problem because they found an alternate method, not because they forgot to do the sub-problem. TSR was calculated by dividing the number of successful codes for a sub-problem by the total number of codes (except for the “not required” code). The individual TSR values for each sub-problem were then averaged into a score for each student. This score was the value used in this paper.

The interaction between the cognitive variables and the students’ problem solving abilities (as measured by TSR), were measured using Spearman’s correlation coefficient, also known as Spearman’s rho (r_s), a non-parametric correlation method. All calculations were performed using SPSS 20. Non-parametric statistical methods were used because the number of students in the study was not large enough to produce a smooth normal distribution. Multi-variate methods could not be used, as the only methods available are parametric.

Results and Discussion

To answer the research question, the correlations between quantitatively measured cognitive variables (Table 3) and students problem solving performances in stoichiometry, evaluated through think-aloud protocols involving solutions of 25 questions, were investigated. Descriptive statistics for all cognitive tests are given in Table 4, along with results of the think-aloud protocol scores as measured by total success rate (TSR). All scores are given out of a maximum possible of 100% except for the DBT scores, which, in theory, have no maximum.

Table 4. Descriptive statistics for the cognitive ability tests

	N	Minimum	Maximum	Mean	SD ^a
TSR	17	20.5	86.0	69.9	17.0
LT	17	61.9	95.2	80.5	8.9
TOLT	17	40.0	100.0	75.3	19.7
DBT	17	3.0	8.0	5.6	1.4
BPCI	17	55.7	90.0	74.6	7.5
MC-AT	17	31.1	97.8	69.7	20.8

^a. Standard deviation

Descriptive Statistics for the LT and DBT

The Longeot test was used to measure the students’ cognitive development; the minimum score needed to be considered a formal thinker was 55%. As can be seen in Table 4,

all students in the study scored above 55 and thus were all at a formal operational stage of cognitive development. This meant that the students were capable of dealing with abstract concepts. This is consistent with Ward et al's (1981) findings that most college students are at the formal operational stage of cognitive development.

The results of the DBT indicated that the study's students' working memory capacity, on average, was lower than that of the general population. For the DBT, different numbers with the varying numbers of digits were selected by the authors. The number of digits used in the test ranged from 2 to 11. However, none of the students in the study were able to recall the longest string of digits, 11. The longest string of digits remembered was 8 and the lowest one was 3, with a mean of 5.6. This was 1.4 digits less than would be expected for an average person (Opdenacker et al., 1990). This observed deviation from the mean DBT result is likely a consequence of the small cohort (17 students).

Observed Correlations with Cognitive Variables

The analysis of the cognitive variables (Table 5) revealed that two of the five cognitive variables, formal (proportional) reasoning ability and mole concept were significantly correlated to students' problem solving ability in stoichiometry (as measured by TSR), with the MC-AT the most strongly correlated. Chandran, Treagust, and Tobin (1987) did a similar research and also found statistically significant correlations between formal reasoning, prior knowledge, and variations in chemistry achievement. In their research, memory capacity (measured by FIT – Figural Intersection Test) did not show a significant role in chemistry achievement. This finding differed from Overton and Potter (2008, 2011) who found that memory capacity was significantly correlated with achievement in chemistry. They also found that working memory capacity, as measured by the DBT, did not correlate with chemistry success, which agrees with the current findings.

Table 5. Non-parametric correlations (Spearman's rho) between various cognitive variables and students total success rate (TSR) in solving stoichiometry problems

	Correlation Coefficient^a	Sig. (2-tailed)
Test of Logical Thinking	.501	.040
Digits Backwards Test	<i>.234</i>	<i>.366</i>
Mole Concept Achievement Test	.866	.000
Longeot Test	<i>-.012</i>	<i>.964</i>
Berlin Particle Concept Inventory	<i>.319</i>	<i>.212</i>

^aSignificant correlations (at 95% confidence level or greater) are in bold; non-significant correlations are in italics. (N = 17 for all correlations.)

The Importance of the Mole Concept

The correlation coefficient ($r_s = .866$, $p < .001$) for the Mole Concept Achievement Test (MC-AT) is large and significant at the 99.9% confidence level. Similar to the above results, many researchers have stressed the importance of the mole concept for success in chemistry (Duncan & Johnstone, 1973; Furio, Azcona, & Guisasola, 2002; Furió, Azcona, Guisasola, & Ratcliffe, 2000; Kolb, 1978; Krishnan & Howe, 1994; Larson, 1997). The very high significant correlation coefficient between the students MC-AT scores and the TSR's (total success rates) accounts for 75% of the observed variance and once again revealed the close association between conceptual understanding of the mole concept and stoichiometric problem solving success in chemistry.

MC-AT is also significantly correlated with the TOLT ($r_s = .568$, $p < .01$, one-tailed), in addition to the significant correlations with the Total Success Rate (TSR), which may mean that someone with a good understanding of the mole concept most likely has a good logical thinking ability. However, it is possible that the skills needed to successfully complete the TOLT are similar to the skills needed to complete the MC-AT.

The Role of Formal Reasoning

A significant correlation was observed between students' TOLT scores and their performances in stoichiometric problem solving ($r_s = .501$, $p < .05$; Table 5). This is consistent with other researchers who have found the formal reasoning ability measured by the TOLT to be a good predictor of chemistry achievement (Lawson, Renner & Karplus, 1975; Sanchez & Betkouski, 1986; Trifone, 1987).

Although the correlation for the Test of Logical Thinking (TOLT) had a smaller coefficient than that observed for the MC-AT, it was significant at the 95% confidence level. Having the ability to reason logically and proportionally appears to be an important characteristic correlated to students' problem solving ability in stoichiometry. Students have to reason logically in order to solve stoichiometry problems, which may be driving this correlation.

Other Cognitive Variables

The remainder of the cognitive variables measured in this study (i.e., cognitive development, working memory capacity, and understanding of particulate nature of matter) may have affected the students' performances, but were not observed to correlate significantly with student success. If there is a correlation between these cognitive variables and students' ability to solve stoichiometric problems, the effect size was likely too small to be measured in a group of 17 students.

Cognitive Variables and the Sub-Problems

The final tests carried out were correlations between the cognitive variables and the sub-problems (Table 2) used in solving stoichiometric problems (Table 6). Since the total success rate (TSR) is the combination of all sub-problems solved while doing a stoichiometry problem, the correlations with individual sub-problems may provide additional information about the nature of those correlations.

Table 6. Non-parametric correlations (Spearman's rho) between various cognitive variables and sub-problems^a used in solving stoichiometry problems

	MC-AT		TOLT		BPCI		DBT		LT	
	Correlation Coefficient	Sig. (2-tailed)	Correlation Coefficient	Sig. (2-tailed)	Correlation Coefficient	Sig. (2-tailed)	Correlation Coefficient	Sig. (2-tailed)	Correlation Coefficient	Sig. (2-tailed)
WEQ	<i>.310</i>	<i>.226</i>	<i>.414</i>	<i>.099</i>	.488	.047	<i>-.189</i>	<i>.468</i>	<i>-.024</i>	<i>.928</i>
BEQ	.508	.037	.497	.042	.640	.006	<i>.079</i>	<i>.762</i>	<i>.284</i>	<i>.269</i>
MP	.557	.020	<i>.375</i>	<i>.138</i>	<i>.288</i>	<i>.263</i>	<i>.025</i>	<i>.923</i>	<i>.432</i>	<i>.083</i>
EF	<i>.096</i>	<i>.714</i>	<i>-.015</i>	<i>.956</i>	<i>-.417</i>	<i>.096</i>	<i>.371</i>	<i>.142</i>	<i>.244</i>	<i>.345</i>
MF	<i>.411</i>	<i>.101</i>	<i>.302</i>	<i>.238</i>	<i>.318</i>	<i>.214</i>	<i>-.115</i>	<i>.660</i>	<i>.414</i>	<i>.099</i>
LR	<i>.383</i>	<i>.130</i>	<i>.054</i>	<i>.836</i>	<i>.080</i>	<i>.761</i>	<i>.003</i>	<i>.991</i>	<i>-.029</i>	<i>.912</i>
PY	.572	.016	<i>.175</i>	<i>.502</i>	<i>.113</i>	<i>.667</i>	<i>.305</i>	<i>.234</i>	<i>-.080</i>	<i>.760</i>
MC	.603	.010	<i>.383</i>	<i>.129</i>	<i>.336</i>	<i>.187</i>	<i>-.039</i>	<i>.883</i>	<i>.204</i>	<i>.432</i>
SR	.597	.011	<i>.302</i>	<i>.238</i>	<i>.075</i>	<i>.775</i>	<i>.191</i>	<i>.463</i>	<i>.242</i>	<i>.349</i>

^a Sub-problems are as follows: writing chemical equations (WEQ), balancing chemical equations (BEQ), mass percent (MP), empirical formula (EF), molecular formula (MF), limiting reagent (LR), percent yield (PY), mole concept (MC), and stoichiometric ratio (SR). Significant correlations (at 95% confidence level or greater) are in bold; non-significant correlations are in italics. (N = 17 for all correlations.)

The Significance of Conceptual Understanding of the Mole Concept

The conceptual understanding of the mole concept appeared to be the statistically most significant variable affecting the students' success. The MC-AT correlated significantly with five of the nine of the sub-problems in stoichiometry. As expected, it showed the highest correlation with the mole concept (MC) sub-problem ($r_s = .603$, $p < .05$; Table 6). Having a good conceptual understanding of the mole concept correlates positively with students' problem solving performance in stoichiometry. Students have to have good knowledge of the mole concept in order to show success in solving the stoichiometry problems. This is not surprising as the mole concept (MC) is the most frequently used sub-problem in solving stoichiometry problems. Mastery of this concept, then, is essential to success in solving stoichiometry problems. MC was not, however, significantly correlated to any of the other cognitive variables.

Other sub-problems with which the MC-AT showed significant correlations were stoichiometric ratio (SR), balancing chemical equations (BEQ), mass percent (MP), and percent yield (PY). The first two correlations, SR and BEQ, are to be expected, as the idea of a constant molar ratio is required for understanding how to use the stoichiometric ratio (or even for knowing that the SR is needed) and for understanding how to properly balance a chemical equation. It is not known why the conceptual understanding of the mole concept is correlated with the mass percent or the percent yield, though it is likely that the same skills that allow students to perform well on those sub-problems also allow students to do better on the MC-AT. The mole concept is also a more conceptually difficult model than calculating percents, so it is reasonable to expect that MP and PY are well within the ability of students who perform well on the MC-AT.

TOLT, Formal Reasoning Ability, and Unexpected Results

The second cognitive variable showing a statistically significant correlation with a student's success in a sub-problem is the formal reasoning ability, as measured by the TOLT. It is interesting to note that the TOLT (Test of Logical Thinking) scores do not correlate with the attempt success rates (ASR's) for the stoichiometric ratio (SR) sub-problem. This is peculiar as the TOLT is designed to measure a combination of all different logical reasoning abilities, *including* the students' proportional reasoning ability, and the SR can be understood as a proportion. Proportional reasoning ability is seen as crucial for students to be successful in chemistry topics, such as stoichiometry and gas laws, where ratios are used (Chandran et al., 1987). It is possible that, because the TOLT has just two questions targeted at measuring proportional reasoning, it is not valid to use the overall TOLT score as a proxy for proportional reasoning ability.

Correlations with the Understanding of Particulate Nature of Matter

Although a significant correlation between the students' understanding of particulate nature of matter and students' overall performances (Total Success Rates) in problem solving was not observed, there were significant correlations between BPCI scores and two sub-problems: writing chemical equations (WEQ) and balancing chemical equations (BEQ). It appears that the understanding of particulate nature of matter is important in order to be successful in writing chemical equations ($r_s = .488$, $p < .05$) and balancing them ($r_s = .640$, $p < .01$).

This finding seems consistent with other researchers' perceptions and findings. Many educators (Gabel & Bunce, 1994; Nakhleh & Mitchell, 1993; Wolfer & Lederman, 2000) have suggested that students' lack of understanding of the particulate nature of matter makes solving problems difficult, especially the problems involving chemical reactions and gas laws.

For the relation between the stoichiometry and particulate nature of matter, Gabel and Bunce (1994) state that some problems in stoichiometry can be solved without comprehending particulate nature of matter, but a good understanding of the particle model can help students grasp chemical reactions and appreciate the quantitative relationships among the substances involved in reactions.

Working Memory Capacity and Problem Solving

No significant correlations were observed between working memory capacity and any sub-problem. This finding was not very surprising due to similar reported results in the literature. Although there are some studies (Johnstone & El-Banna, 1986) in which students' working memory capacities show a significant correlation with students' achievement in chemistry, there are more recent studies (Chandran et al., 1987; Opdenacker et al., 1990) in which the working memory capacities are not significantly correlated with the students' achievements in chemistry. The findings of this study were consistent with the findings of Opdenacker et al. (1990). The highest and the lowest working memory capacities of the students in the study were eight and three respectively, with a mean of 5.6, which was nearly identical to Opdenacker et al.'s (1990) observations.

While no significant correlations were observed, this does not necessarily mean that working memory is irrelevant to stoichiometry or problem solving. One reason for the lack of correlation could be the lack of variation in students' performance with respect to the DBT scores in the study. Most students obtained a score of 5 or 6, and the standard deviation was relatively small (1.4). In this limited range, DBT scores might not appear to be statistically significantly related to achievement in stoichiometry. This factor may limit the DBT's discriminating power. Since students were writing down the problems as they worked them out, working memory may not have been relevant. Specifically, the paper on which the students were writing could have served the same purpose as working memory—storing information and calculations until needed. It is also possible that the stoichiometry problems used to test the students did not provide a sufficient cognitive load and thus working memory was not a factor. If either were the case, no correlations with working memory could be expected.

Students' Cognitive Development

Similar to the findings with the working memory capacity, no significant correlation was observed between students' success with the sub-problems of stoichiometry and students' cognitive development. These results made sense when the LT results are examined; the average score was 81.5 and standard deviation was low (8.6). All students were measured to be at the formal operational stage, which means they could deal with abstract concepts. Since there was little measured difference between students' cognitive development, the cognitive variable could not be used to predict student success in stoichiometry or chemistry for this study.

Inter-Test Correlations

To test to what extent the tests measured the same underlying variables, Spearman's correlation coefficients were measured between each of the selected cognitive variable tests. It was assumed that if there was any correlation, that correlation would be positive, as the cause of any increase in one cognitive variable may result in the increase of another as well. Only two correlations were shown to be significant at the 95% confidence level (one-tailed). The BPCI was significantly correlated with the MC-AT ($r_s = .468$, $p < .05$), which accounted for 22% of the variance in each test. This was expected, as both tests require some chemistry knowledge to score well. The MC-AT was also significantly correlated with the TOLT ($r_s =$

.568, $p < .01$), which accounted for 32% of the variance in each test. The significance of this is discussed below. Neither of these correlations was large enough to expect that they measured the same thing. No other significant correlations between the cognitive variable tests were observed, which suggested that each of the tests measured a different aspect of cognitive function.

Conclusions

The investigation of the cognitive variables indicated that only formal (proportional) reasoning ability and understanding of mole concept were good predictors of students' success in stoichiometry. Although understanding of particulate nature of matter did not show correlation with success in solving general stoichiometry problems, it did show statistically significant correlations with writing and balancing chemical equations. The other measured variables (working memory capacity and cognitive development), on other hand, appeared to have no significant correlation with undergraduate students' achievements in solving stoichiometry problems. The lack of correlation with these cognitive variables does not necessarily mean that they do not play a role in students' success in stoichiometry, only that no correlation was detected at this time. All of the students were measured to be at the same level of cognitive development, so there was no way to differentiate students with this variable. It is also possible that the stoichiometry problems or the way they were presented and run did not put sufficient demand on working memory and, thus, working memory did not register as a significant factor.

Implications for Classroom Instruction

In light of the findings, observed significant correlations between formal (proportional) reasoning ability, conceptual understanding of mole concept, a meaningful understanding of particulate nature of matter and students' success in stoichiometric problem solving, some strategies around each cognitive variable are recommended for the educators.

Emphasis on Conceptual Understanding of Mole Concept

Chemistry teachers should strive to promote conceptual understanding if they want their students to be more successful in solving problems. It is worth developing new instructional techniques to facilitate and enhance students' learning experience by focusing on concepts and highlighting the links between different concepts (Gabel & Bunce, 1994). Among the promising instructional methods, the guided inquiry based approaches would be beneficial to both science and non-science majors and encourage them to learn the processes necessary to be successful not only in science classrooms but wherever inquiry and discovery are required (Phelps, 1996). Guided inquiry methods allow students to construct their own information and conclusions through cooperative investigations with two or more students, which has been shown to improve conceptual understanding, such as understanding of the mole concept (Eberlein et al., 2008; Moog & Spencer, 2008; Vygotsky, 1978).

Taking into account of Particulate Nature of Matter

Although understanding of the particulate nature of matter did not show significant correlations with any of the sub-problems other than WEQ and BEQ, it is still considered as one of the most important factors in learning chemistry (Bunce & Gabel, 2002; Harrison & Treagust, 2002). Thus, science educators should assist their students to comprehend the particulate nature of matter and help them to use this theory, not just for science problems they are dealing in the classroom, but also for many natural phenomena they observe in everyday life.

There are several difficulties regarding the use of particulate nature of matter. One of the common problems is that students do not use the particle model unless they are explicitly told to do so. Studies in the area of students' alternative conceptions have indicated that isolating school science from students' real-life could make students develop two unconnected knowledge systems related to science: one is used to solve science problems in schools, and the other used for everyday life (Williamson et al., 2004). Lewis and Linn (1994) found that encouraging students to combine their experiences in the everyday world with scientific examples and explanations helps to prevent compartmentalization.

Considering Students' Formal Reasoning

Other research projects have also indicated that formal reasoning ability of learners correlates with students' achievement in chemistry (Huddle & Pillay, 1996). Studies emphasize that students need to have a good level of abstract thinking in order to understand some chemistry concepts such as mole concept, particulate nature of matter, and the meaning of chemical equations, and must be able to make connections among three different levels of chemistry knowledge (i.e., macroscopic, microscopic, and symbolic) which leads to success in problem solving (BouJaoude & Barakat, 2003; BouJaoude, Salloum, & Abd-El-Khalick, 2004).

Herron (1978) believes that use of concrete models, illustrations and diagrams can facilitate the understanding of abstract concepts and help students who lack of formal reasoning ability. Molecular models (Gabel, Sherwood, & Enochs, 1984), illustrations (Cantu & Herron, 1978), pictorial representations (i.e., maps or flow-charts) for the solution of typical stoichiometry problems (Ault, 2001), models of physical processes (Howe & Durr, 1982), computerized instruction with more visual materials (Yalçinalp et al., 1995) have all proven efficacious in improving students' achievement in chemistry. Students may also benefit from the use of cognitive conflict, in which students can be challenged to facilitate their development in correct reasoning (Trifone, 1987).

Limitations to the Study

The biggest limitation in this study was the number of subjects, just seventeen non-major undergraduate students. A larger sample of students may have revealed more statistically significant phenomena that are only measurable in larger samples. All students were taken from one university in the Midwest of the United States, and all of these students were science majors. This cohort may have been exceptionally good or exceptionally poor at stoichiometry, as so the results may not be applicable to all students.

Recommendations for Future Research

We believe it is worth doing new research with more students to investigate the influence of cognitive variables, especially the working memory capacity of students and cognitive development, on solving stoichiometric problem solving. In this study, one test was used for each variable. In future research, along with the DBT and LT tests, the other tests designed to measure the same cognitive variables could be used to have alternative data on the same cognitive variables. A comparison of students majoring in chemistry with those not majoring in chemistry (as in the current study) may also reveal differences in student approaches to stoichiometry.

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