AN EXPLORATORY INVESTIGATION OF SOURCES OF INDIVIDUAL DIFFERENCES IN CHEMISTRY PERFORMANCE: THE POTENTIAL ROLE OF VISUAL AND VERBAL WORKING MEMORY AND STUDENT AFFECT IN CHEMISTRY PROBLEM SOLVING

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By

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An Exploratory Investigation of Sources of Individual Differences in Chemistry Performance: The Potential Role of Visual and Verbal Working Memory and Student Affect in Chemistry Problem Solving

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This thesis was prepared under the direction of the candidate's thesis advisor, Dr. Steven A. Hecht, Department of Psychology, and has been approved by the members of his supervisory committee. It was submitted to the faculty of the Charles E. Schmidt College of Science and was accepted in fulfillment of the requirements for the degree of Master of Arts in Psychology.

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Abstract

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This was an exploratory study of factors that predict individual differences in chemistry learning. Consistent with cognitive learning theory, working memory was assumed to be an important predictor of chemistry knowledge. Measures of chemistry affect, cognitive ability, demographics and mathematical ability were examined in relation to visual/schematic and algebra-like stoichiometry chemistry word problem solving ability and strategy use. 139 undergraduate students (91 females, 48 males) at a major Southeastern university participated in this study (Age ranged from 18 to 39 years (M = 20.70 years of age)). Perceived usefulness of the chemistry material, mathematical ability, GPA, and SGPA uniquely predicted conceptual stoichiometry problem solving ability.

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Introduction

Chemistry is a symbolic and visual science. Chemistry problems take on a variety of representations. Chemical representations such as molecular structures and atomic models are partially schematized and partially iconic diagrams that depict abstract concepts and apply conventions to illustrate both the components and their organization (Hegarty, Carpenter, & Just, 1991). Schematic and algebraic representations are two of the more common formats that chemistry problems take. These different ways of representing information reflect the underlying nature of chemistry and the learning characteristics and mechanisms that often accompany successful chemistry performance and mastery. Mutiple representations also provide great benefit in learning and cognitive performance (Bransford et al,, 1999). Advantages of abstract representations have been demonstrated in the context of algebra problems involving mixtures. Singley and Anderson (1989) presented one group of participants with pictures of specific mixtures (picture group) while the other group was shown abstract tabular representations of mixtures that combined pictoral and verbal descriptions and highlighted the underlying mathematical principles of mixture problems (abstract group). Subjects trained with specific task components and provided with basic principles underlying the tasks (picture group) could do the specific tasks well, but they could not apply their learning to new problems. The participants exposed to abstract training showed transfer to new problems that involved analogous mathematical relations. In short, developing a suite of representations enables learners to think flexibly about complex domains (Spiro et al., 1991). In the chemistry domain, Bodner and Domin (1996) conclude a review on the role of representations in problem solving in chemistry noting "successful problem solvers construct significantly more representations while solving a problem than those who aren't successful." The representations are either visual or verbal in nature.

I first outline the kinds of chemistry problems that will be focused on in the study. Next, I present relevant research illustrating links between chemistry problems and working memory resources. Finally, proposed research methods will be presented.

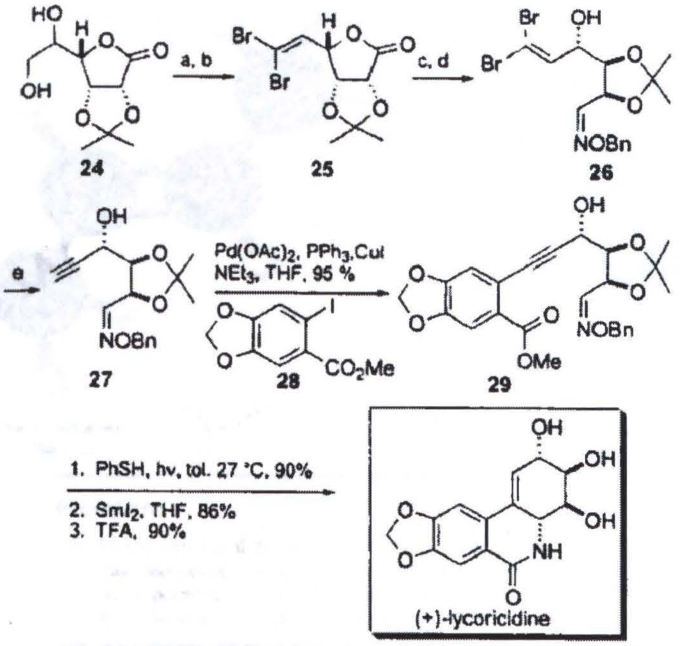
Representations of Chemistry Problems: Visual Schematic

Schematic problems present information in a graphical, diagrammatic fashion. A typical example of a schematic laboratory task involves outlining a multiple-step synthesis of an organic compound (Figure 1).

To visualize and describe the synthesis procedure, chemists always sketch structures of reactants (starting chemicals) and products, and draw symbols, arrows, and equations to describe chemical processes (Kozma et al., 2000). These chemical representations spatially present the imagery of particles and their geometric shape in two dimensions and compose a spatial language (Balaban, 1999; Habraken, 1996; Nye, 1993). They present information that may not be easily understood otherwise (Larken & Simon, 1987) and allow chemists to think visually and convey information efficiently through a form of schematic visual display.

Schematic representations have also been used for communicating concepts to students of chemistry. Secondary school and college-level curricula and textbooks use a variety of visual representations to introduce fundamental chemical concepts (Noh & Scharmann, 1997). Figure 2 shows an example of using visual representations to explain isomerism in chemistry. To identify geometric isomers, which have the same chemical formula but different structures and properties, students are required to translate a chemical formula into its molecular structure(s), visualize the possible three-dimensional (3D) configurations, and compare those configurations. Therefore being able to comprehend and mentally manipulate chemical representations is critical for students to understand the content and conduct advanced research.

It is not always easy to link the molecular understanding to conceptual understandings. This point was well made by Johnstone (1982) when he pointed out that understanding chemistry involves working at three levels: the level of the macroscopic (phenomena which are open to the senses, such as change of color in a solution); the level of the sub-microscopic (the molecular level, changing of elements in a molecule); and the level of the symbolic (the use of chemical and algebraic equations and schematic representations to represent or describe a chemical process over time). The point that Johnston was making is that it is difficult for the new learner to operate easily at all three levels simultaneously. However, in the learning of chemistry, it is customary to present the material at the start in symbolic form (symbols and equations) with reactions being interpreted at the molecular (functional group) and electronic level.



[a] Key: (a) $NaIO_4$, CH_2Cl_2. (b) CBr_4, PPh_3, NEt_3, 80% over two steps. (c) L-Selectride, Et_2O, −78 °C. (d) HCl·H_2NOBn, pyridine, 90% over two steps. (e) ^nBuLi, Et_2O, −90 °C, 93%.

Figure 1. A synthesis scheme from an article by Keck, Wager, and Rodriquez (1999). Reprinted with permission from Journal of the American Chemical Society, 121(22), 5179. Copyright 1999 American Chemical Society.

A mechanistic approach seeks to show why the various groups of organic compounds behave in the way observed; it attempts to present a bewildering array of information in such a way than an underlying structure and rationalization can be perceived and understood.

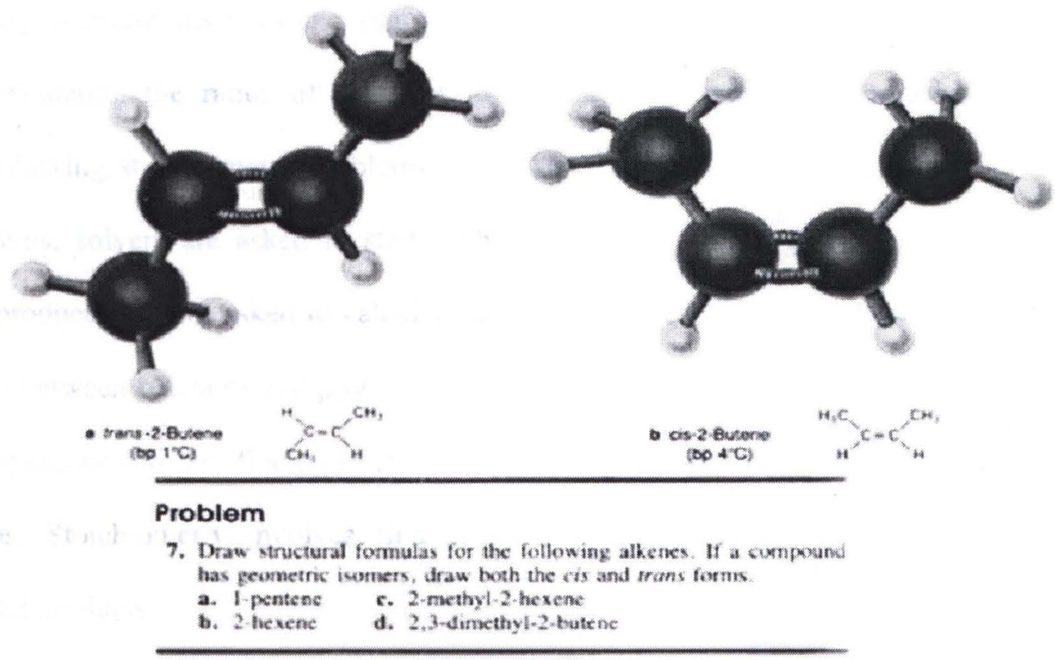


Figure 2. Representations of geometric isomers and a relevant problem in a chemistry textbook for high school students. From *Addison-Wesley Chemistry* by Antony C. Wilbraham, Dennis D. Staley, and Michael S. Matta © 1987 by Addison-Wesley Publishing Company, Inc. Published by Pearson Education, Inc., publishing as Pearson Prentice Hall. Used by permission.

In order to build a foundation by which further chemistry knowledge is attained a student must learn the 'alphabet' of chemistry (usually at the level of the symbolic; the use of chemical and algebraic equations to represent a phenomena). The student then gradually comes to understand the grammar (mechanisms or typical behaviors and reactions) of classes of chemical compounds and is encouraged to ask such questions as, "what class of organic compound is this?" "what kind of reaction can I expect to undergo?" "are there any specific aspects to the reactivity of the compound that I need to bear in mind when deciding on the likely product(s) of the reaction?" This learning process is similar to algebraic thinking, particularly when components of an equation need to be derived from a word problem.

Chemistry learning involves the processing of symbolic relations. Stoichiometry involves calculating the ratios of reactants to the ratios of products in a balanced equation. Working stoichiometry problems is similar to working algebra equations. In both problems, solvers are asked to start with one symbol or unit (e.g., grams of a particular product) and are asked to calculate how many units (moles: the basic unit of comparison between reactants and products) of a particular reactant are needed. Solving algebraic equations involves finding relationships between quantities; algebra is the logic of relations. Stoichiometry involves finding the relationship between quantities of reactants and products.

Representations of Chemistry Problems: Verbal Symbolic Manipulation

We turn next to how we represent verbally what happens to atoms and molecules (the basic chemical building blocks) in a chemical reaction, a process in which a substance (or substances) is changed into one or more new substances. In order to communicate with one another about chemical reactions, chemists have devised a standard way to represent reactions using chemical equations. A chemical equation uses chemical symbols to show what happens during a chemical reaction. Consider what happens when hydrogen gas (H2) burns in air (which contains oxygen, O2) to form water (H2O). This reaction can be represented by the chemical equation

$$H2 + O2 \Rightarrow H2O$$

Where the "plus" sign means "reacts with" and the arrow means "to yield." Thus, this symbolic expression can be read: "Molecular hydrogen reacts with molecular oxygen to yield water."

This equation is not complete, however, because there are twice as many oxygen atoms on the left side of the arrow (two) as on the right side (one). The equation is thus unbalanced; we must have as many atoms after the reaction ends as we did before it started. We can balance the equation for the combustion of hydrogen by placing the appropriate coefficient (2 in this case) in front on H2 and H2O, without changing any subscripts:

$$2H2 + O2 \Rightarrow 2H2O$$

The balanced chemical equation shows that "two hydrogen molecules can combine or react with one oxygen molecule to form two water molecules." Since the ratio of the number of molecules is equal to the ratio of the number of moles (coefficients), the equation can also be read as "2 moles of hydrogen molecules react with 1 mole of oxygen molecules to produce two moles of water molecules." Balancing a chemical equation involves many of the cognitive operations crucial for a mastery of algebra: a sense for proportionalities, ratios, and dealing with equalities.

Another type of chemistry problem that involves algebraic type transformations and manipulations of systems of equations is stoichiometry. A basic question raised in the chemical laboratory is, "How much product will be formed from specific amount starting materials (reactants)?" Or in some cases the reverse may be asked "How much starting material must be used to obtain a specific amount of product." To interpret a reaction quantitatively knowledge of molar masses and the mole concept, just discussed, are necessary. The periodic table gives us access to the atomic weight of all atoms. For example, the mass of hydrogen is 1.008. Thus in the combustion of hydrogen example above 2 moles of H2 have a molar mass of 4.032. Oxygen has an atomic mass of 16.00 and 1 mole of O2 has a molecular mass of 32.00. Stoichiometry is the quantitative study of reactants and products in a chemical reaction.

The mole method of stoichiometry simply states that the stoichiometric coefficients in a chemical equation can be interpreted as the number of moles of each substance. For example, the combustion of carbon monoxide in air produces carbon dioxide:

$$2CO + O2 \Rightarrow 2CO2$$

For stoichiometric calculations we would read this equation as "2 moles of carbon monoxide gas combine with 1 mole of oxygen gas to form 2 moles of carbon dioxide gas.

The mole method consists of the following steps:

1. Write correct formulas for all reactants and products, and balance the resulting equation.
2. Convert the quantities of known substances to (usually reactants) moles.
3. Use the coefficients in the balance equation to calculate the moles of the sought or unknown quantities (usually products)
4. Using the calculated number of moles and the molar masses, convert the unknown quantities to whatever units are required (usually grams)

5. Check that your answer is reasonable in physical terms

For stoichiometry problems 2 moles CO are said to be "equivalent to" 1 mole O2 (because they react with one another in a fixed proportion). This convention allows for the writing of unit factors (2 mol CO/1 mol O2 = 1 or 1 mol O2/2 mol CO = 1). Similarly, since 2 moles of CO (or 1 mole O2) produce 2 mols CO2, we can say that 2 moles of CO (or 1 mole of O2) are equivalent to 2 moles of CO2).

The algebraic nature of stoichiometry problems is nicely illustrated by an example shown in Appendix A, thus illustrating that algebra performance may be correlated with working memory performance.

Chemistry learning thus, in part, involves the understanding of symbolic relations. Stoichiometry involves calculating the ratios of reactants to the ratios of products in a ballanced equation. Working stoichiometry problems is similar to working algebra equations. In both problems, solvers are asked to start with one symbol or unit (e.g., grams of a particular product) and are asked to calculate how many units (moles: the basic unit of comparison between reactants and products) of a particular reactant are needed to balance the chemical equation. Solving algebraic equations involves finding relationships between quantities; algebra is the logic of relations. Stoichiometry involves finding the relationship between quantities of reactants and products

Working Memory- The Baddeley Model

Prior to detailing the way that working memory is involved in chemistry problem solving, it is useful to first describe briefly the model of working memory that this study is based on.

Within cognitive psychology the term "working memory" has been adopted to cover the system or systems involved in the temporary maintenance and manipulation of information. Atkinson and Shifrin (1968) applied the term to a unitary short-term store, in contrast to the proposal of Baddeley and Hitch (1974), who used it to refer to a system comprising multiple components. They emphasized the functional importance of this system, as opposed to its simple storage capacity.

Baddeley and Hitch (1974) proposed that the earlier unitary concept should be elaborated into a three-component system. This comprises a limited capacity attentional controller, the central executive, aided by two "slave" subsystems, one concerned with acoustic and verbal information, the phonological loop, and the other performing a similar function for visual and spatial information, the visuospatial skectchpad.

The phonological loop was proposed to give an acount of the substantial evidence that had accumulated concerning short-term verbal memory, typically involving the classic digit span procedure. The articulatory loop was assumed to comprise two components, a phonological store and an articulatory rehearsal store. Traces within the store were assumed to decay over a period of about two seconds unless refreshed by rehearsal, a process akin to subvocalization and one that is dependent on the second component, the articulatory system (Baddeley & Hitch, 1974)[1].

The store was assumed to be reflected in the phonological similarity effect, whereby immediate serial recall of items that are similar in sound (e.g., the letters B, V, G, T, C, D) is poorer than that for dissimilar items (e.g., F, K, Y, W, M, R; Conrad & Hull, 1964). Similarity of meaning, however, typically has little effect in the standard immediate serial recall paradigm (Baddeley, 1966a). The reverse is true of the multitrial long-term learning of 10-item sequences, which appears to depend principally on semantic rather than acoustic coding (Baddeley, 1966b).

The articulatory rehearsal component was proposed to give an account of the word length effect, whereby immediate serial recall is a direct function of the length of the items being retained (Baddeley, Thompson, & Buhanan, 1975). Hence, a sequence such as *sum, pay, wit, bar, hop* is much more likely to be recalled correctly than *helicopter, university, alligator, opportunity*. This was originally proposed to reflect the slower rehearsal of longer words, which allows greater forgetting. It has also been claimed to result from forgetting during the process of recall, which again tends to be slower with longer words (Cowan et al., 1992; Dosher & Ma, 1998). It now appears that both of these processes are important (Baddeley, Chincotta, Stafford, & Turk, 2002). Consistent with this view is the fact that when rehearsal is prevented by articulatory suppression, the

[1] Articulatory was changed to phonological to emphasize the fact that this subsystem is not limited to the articulatory component.

repetition of an irrelevant sound such as the word *the*, the word length effect disappears (Baddeley, 1974).

The process of subvocalization also seems to play an important role in registering visually presented material within the phonological loop. Hence, articulatory suppression eliminates the effect of phonological similarity when material is presented visually but not with auditory presentation, which is assumed to provide direct access to the phonological store (Baddeley, Lewis, & Vallar, 1984; Murray, 1968). Finally, immediate serial verbal memory is impaired by the presentation of irrelevant auditory material that the participants are instructed to ignore (Colle & Welsh, 1976; Salame & Baddeley, 1982). The disruptive effect is not limited to speech, being also found in fluctuating tones, although not when white noise varies in loudness (Jones, 1993). Precise interpretation of the irrelevant sound effect remains equivocal (Baddeley, 2000; Jones & Tremblay, 2000; Neath, 2000).

The strength of the phonological loop model resides in the fact that it can offer a simple and coherent account for a relatively complex set of data. It has also helped explain certain neuropsychological deficits (e.g., patients who appear to have impaired short-term memory (STM), as reflected by low digit span, coupled with normal long-term memory (LTM; Shallice & Warrington, 1970; Vallar & Baddeley,1984)). The process of subvocal rehearsal has been further elucidated by the study of patients with different speech and language deficits. Patients who have lost peripheral control of their speech musculature are still able to rehearse (Baddeley & Wilson, 1985), while those who have lost the capacity to construct a speech-motor plan show no such capacity (Caplan & Waters, 1995). This suggests that rehearsal should be regarded as reflecting the central control of speech rather than the overt capacity to articulate. Lastly, Baddeley, Gathercole, and Papagno (1998) have argued that the phonological loop has evolved to support the acquisition by children of their native language and that it plays an important role in adult second-language learning.

Two other important aspects of the phonological loop warrant discussion. The first concerns the interaction between the phonological loop and LTM. Baddeley, Gathercole, and Papagno (1998) proposed that an important evolutionary function of the loop is to facilitate the acquisition of language by maintaining the representation of a new word in order to optimize learning. The impairment of foreign language acquisition in patients with a classical STM deficit (Baddeley, Papagno, & Vallar, 1988) and normal children whose capacity to hear and repeat back an unfamiliar pseudoword (nonword repitition) predicts level of vocabulary development (Gathercole & Baddeley, 1989) support this position. Children with a specific language impairment (SLI) are found to be particularly impaired on nonword repetition. For example, eight-year-olds with normal nonverbal intelligence, coupled with the verbal development of six-year-olds, showed a level of nonword repetition that was equivalent to that of four-year-olds (Gathercole & Baddeley, 1990).

The visuospatial sketchpad is assumed to be capable of temporarily maintaining and manipulating visuospatial information, playing an important role in spatial orientation and in the solution of visuospatial problems. Logie (1995) assumes that the sketchpad forms an interface between visual and spatial information, accessed either through the senses or from LTM. This mechanism allows a range of channels of visual information channels to be bound together with similar information of a motor, tactile, or haptic nature. Much research over recent years has been concerned with establishing the potential seperability of the visuospatial skethchpads visual and spatial components. There is both behavioral and neuropsychological evidence to suggest an association between spatial STM and the Corsi block-tapping task. In the Corsi block task participants attempt to copy a sequence of movements made by the experimenter in tapping an array of blocks. The visual component is reflected in pattern span. This involves showing the participant a matrix in which half of the cells are filled and require immediate recall or recognition; the size of the matrix is increased to visual span, when errors begin to occur (Della Sala, Gray, Baddeley, Allamano, & Wilson, 1999).

The sketchpad can be disrupted by requiring participants to tap a specified pattern of keys or locations repeatedly, a procedure that impairs the use of visuospatial imagery (Baddeley & Lieberman, 1980). Unattended patterns or visual noise may disrupt the visual component of the system (Logie, 1986; Quinn & McConnell, 1996) and successful visual task performance.

Visual Working Memory and Chemistry Knowledge

Chemistry teachers and educational researchers have recognized the importance of visualization thinking in chemistry. However, a number of questions remain about the role of visual thinking in chemistry. First, to what degree do individual differences in visuospatial abilities predict learning in chemistry? Second, to what extend do conceptual errors in chemistry arise from difficulties in comprehending, translating, and transforming internal and external visual representations?

Before outlining the research on visual thinking in chemistry education, it would be helpful to establish what kinds of visual representations are used in chemistry. Chemical representations such as molecular structures and atomic models are partially schematized and partially iconic diagrams that depict abstract concepts and apply conventions to illustrate both the components and their organization (Hegarty, Carpenter, & Just, 1991). The relationships between visual displays and chemical concepts in neither arbitrary, as is the relation between words and concepts, nor a first-order isomorphism, as is the relation between pictures and their referents (Winn, 1991). Thus, in the continuum of different forms of written information, chemical representations are typically more abstract than pictorial diagrams, but still represent information in an analogical, nonarbitrary fashion. For example, Figure 2 illustrates a partially schematic diagram of two butene molecules in which individual atoms and chemical bonds are schematized to look like balls and sticks. At the same time key concepts are represented such as the number of bonds that a hydrogen atom has and the geometrical shape of a butene molecule. Using these representations to perform tasks requires a series of cognitive operations, such as recognizing the graphic conventions, manipulating spatial information provided by a molecular structure, and mentally tracking the constraints based on concepts. Thus, it is likely that learning chemistry involves students' visuospatial abilities and performing certain cognitive operations spatially.

Interested in whether spatial abilities affect students' chemistry learning achievement, a series of studies emphasized the role of visuospatial thinking (and visuospatial working memory) by investigating the corrrelation between spatial abilities and chemistry learning.

Spatial visualization involves tests that "reflect processes of apprehending, encoding, and mentally manipulating spatial forms" (Carroll, 1993, p.309). Working memory's role in the encoding, retrieval, and manipulation of visual information suggests that students with poor spatial working memory should be poor at these tasks. An example of such a test is the Purdue Visualization of Rotation Test (see example in figure 3), a commonly used measurement of spatial visualization in chemistry education (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987; Yang, Greenbowe, & Andre, 1999). In this test participants view two rotated versions of an 3D figure, infer the type of transformation between them, and make the same transformation with a new 3D figure (figure 3).

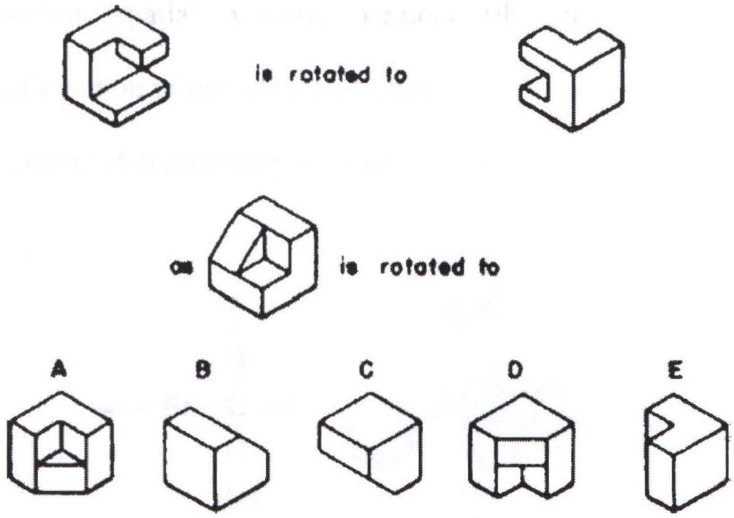


Figure 3. One item from the Purdue Visualization of Rotations Test.

Mental manipulation of spatial representations such as those required on spatial visualization tests are also required in chemistry problem solving. For example, to determine whether dibromomethane (CH2BR2) is a polar molecule (a common high school chemistry task), students typically draw or are shown a schematized two-dimensional (2D) structural formula (figures 4a and 4c). However, the two diagrams could lead to different conclusions unless students mentally or physically create a 3D model of the molecule as in Figures 4b and 4d. In short, the molecule is polar because the resolution of the two vectors, representing electron density, is centered about one atom in the molecule. As this example indicates, making a simple judgement about polarity involves constructing a 3D model from a 2D depiction.

Another factor, closure flexibility, is concerned with the speed of apprehending and identifying a visual pattern, often in the presence of distracting stimuli. It requires students to internally maintain a given pattern and counteract the distracting stimuli.

Student spatial working memory (the ability to encode and manipulate spatial information in the service of a task) should positively correlate with a student's ability to apprehend and identify a visual stimulus embedded in distracting stimuli.

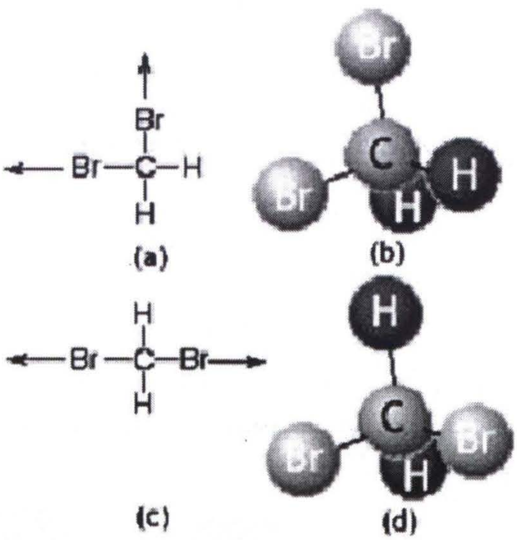


Figure 4. 2D and 3D representations of CH_2Br_2.

Closure flexibility is measured by tasks such as the Find-a-Shape-Puzzle in which people must find simple figures embedded in more complex ones (see example in Figure 5). This factor is also considered related to chemistry problem solving (Bodner & McMillen, 1986; Carter, LaRussa, & Bodner, 1987). The synthesis scheme shown in figure 1 is an example. When considering what chemical reagents are needed to produce compound 25 by using compound 24 as a reactant, chemists first identify visual similarities and differences between the two complex molecular structures. In this case, the structural differences are the disappearance of the two hydroxyl (-OH) groups in compound 24 and the formation of a double bond attached to two bromine atoms (Br) in compound 25. Based on this information, the chemist would decide that bromine is necessary in the reagents for this reaction. Reading an IR (infared), UV (ultaviolet), or NMR (nuclear magnetic resonance) spectrum to decide the structure of a molecule are other tasks that require the apprehension and identification of a visual pattern (molecular structure) in the presence of distracting stimuli. Thus, closure flexibility skills are frequently used in chemists' daily practices.

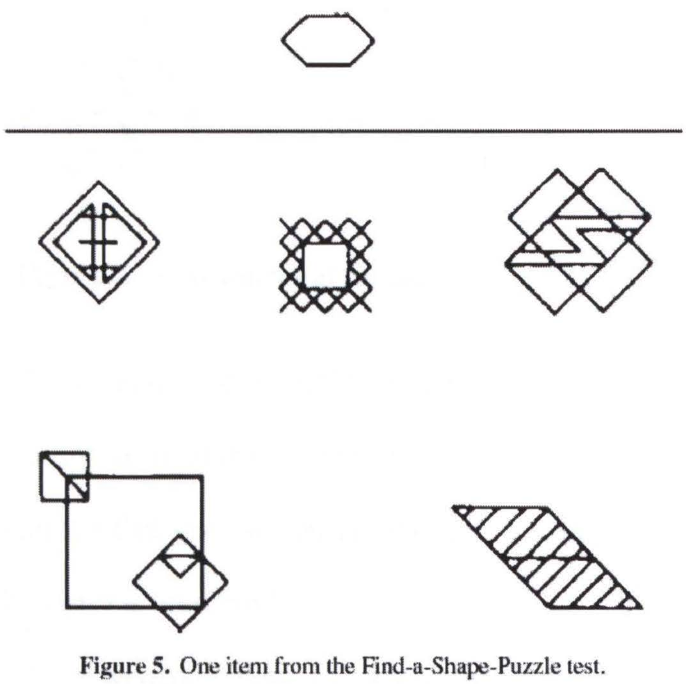


Figure 5. One item from the Find-a-Shape-Puzzle test.

A third factor is spatial relations and one of the examples is the card rotation task. (Barnea & Dori, 1996). Participants must judge which of a series of figures is the same as the target figure. This factor is similar to spatial visualization in that spatial rotations also require mental transformations, but differ in that they involve simpler manipulations (usually within a single step) of 2D objects and tend to emphasize speed (Carroll, 1993).

Chemistry problems related to the identification of isomers (compounds with the same formula but different connectivities) require this kind of spatial reasoning. For instance, to identify whether structures (a) and (b) in Figure 6 represent geometric isomers, students have to mentally rotate the single-bond between the two carbon atoms. Because the figures are superimposable (identical when placed on top of each other) after rotation, they are not isomers but represent the same structure.

(a) (b)

Figure 6. Two structural formulas of C_3H_7Cl.

The examples of spatial ability tests and chemistry tasks described above illustrate how visuospatial thinking may be involved in doing chemistry. In this section, correlational evidence that visuospatial abilities are an important component of student's learning in chemistry is presented.

In a general study of spatial abilities and problem-solving skills, Bodner and McMillen (1986) measured students' chemistry learning achievement in problems with and without obvious spatial components, such as identifying crystal structures and solving stoichiometry problems (finding proportionalities between reactants and products). They found that total scores on the spatial visualization and closure flexibility tests were significantly correlated with performance on all chemistry subtests. That is, visuospatial skills partially explained students' performances on the apparently spatial type of chemistry problems as well as the nonspatial problems (I.e. the stoichiometry problems).

Verbal Working Memory & Chemistry Problem Solving

Verbal working memory (Baddeley, 1990) may be described as the ability to retain and manipulate sequences of digits or words; as when learning a new language or performing digit span tasks. It is thus not a far leap to hypothesize that verbal working memory ability maps onto the ability to solve algebraic equations (Lee et al., 2004). A similar hypothesis may generated, in turn, to describe the relationship between verbal working memory ability and stoichiometry skills. Stoichiometry problems, like algebraic problems, may thus rely heavily on verbal reasoning, verbal rules, and symbolic manipulations.

Working memory's structure (Baddeley, 1999) helps account for differences in fluid working memory capacity (the ability to use working memory to perform tasks). According to Baddeley, working memory provides a temporary storage necessary for a wide variety of tasks such as mental arithmetic, reasoning, and problem solving; It holds and manipulates limited material in the service of a task (e.g., Seven +/–2 items (or meaningful chunks of information) approaches the average memory span (Baddeley, 1999)). Thus, if a student is poor at representing, retaining, and manipulating conceptual information (e.g., cannot group the information contained in a multi-step synthesis problem into a series of meaningful chunks) he may have difficulty understanding how one step logically follows another in synthesis problems. On the other hand, a student who possesses the ability to effectively put chemistry information together into a meaningful framework may find such problems easy to complete. Problem solvers may have difficulty keeping in mind alternatives because multiple possibilities can exceed their working memory capacity (Byrne, 2005; Johnnson-Laird and Byrne, 1991; 2002). They also need to be able to switch their attention between alternative possibilities to reach a solution.

Johnstone (1984) and Johnstone and El-Banna (1986) confirmed that working memory space has a very limited capacity and, when exceeded, this can make learning almost impossible. When this is applied to the learning of organic chemistry, the problems are readily apparent. Take a 'simple' molecule such as CH3CH2COOCH3 (methyl propanoate). If a person who knows no organic chemistry was presented with this symbolic formula for ten seconds and then was asked to reproduce it, the task would probably be well beyond his capabilities. This is simply because the amount of information in the structure is well beyond the working memory space capacity of the learner.

However, another person with some knowledge of organic chemistry might be able to group the (CH3CH2) group as a 'chunk' (with or without the name 'ethyl') and recognize the ester functional group (COO) as a 'chunk' and the final methyl group as a third 'chunk.' This has the potential to reduce the load to three pieces only. Provided the linkages can be appreciated, this gives the person a chance of holding the formula within the capacity of the working memory. This reduces working memory load as more cognitive resources are available for the representation and manipulation of task-relevant information. The efficiency of working memory strongly affects how links can be formed between symbols and verbal referents. For example, in the math domain, simple arithmetic problems and answers seem to be constrained by available working memory resources (Geary, 1996). Geary and others (e.g., Hecht, 2002), have argued that when presented a math problem, the link between that problem and answer is established when working memory resources are used to attend both the problem and answer during problem solving. With increased exposure to a particular math problem and answer, links gradually become established over time. The greater the working memory resources available during problem solving, the faster an individual can form strong links between problems and answers. Strong links between problems and answers in long term memory enable the relatively faster and more accurate retrieval strategies to be used in math. This same process is likely to be used is other domains, such as chemistry. Indeed others have shown that cumulative experience with solving of problems enables retrieval (see Rittle-Johnson & Siegler (1999), Logan (1988). An experienced chemist would thus see the above structure as one unit or 'chunk' (methyl propanoate) and would be able to store, reproduce or manipulate such structures easily within working memory. Perceiving and correctly categorizing the component functional groups (chunks) in the correct order involves a kind of proportional reasoning. If the correct proportions of methyl propanoate's functional groups are not recalled in the correct order, the molecule may be incorrectly identified. This type of proportional reasoning characterizes both stoichiometry and algebra problems.

In sum, working memory refers to some kind of hypothesized limited-capacity mental resource that can be applied to learning, reasoning, and problem solving that require the simultaneous representation and manipulation of information.

No studies to date have explicitly examined the verbal character of stoichiometry problems, or of any other type of chemistry problem. For this reason, in the present study, the relationship between stoichiometry problems and verbal working memory performance will be examined. This will be done by looking at whether stoichiometry performance is associated with verbal working memory performance.

However, the algebraic nature of chemistry problem solving suggests that verbal working memory is closely related to chemistry skills. Algebra problem solving ability has already been demonstrated to correlate with verbal working memory. Lee et al. (2004) examined the relation among working memory, reading abilities, and mathematical performance (algebraic word problems) and whether the contributions to mathematical performance were direct, indirect and mediated by language, or both. Children (mean= 10.7 years) were administered a working memory span based battery (WMTB-C (Pickering & Gathercole, 2001)), an abbreviated IQ test, a reading ability test, and ten algebraic word problems that tested children's understanding of relational concepts: more than, less than, as many as, older than, and concepts testing concepts of proportional reasoning. Three domains of working memory were accessed: central executive, phonological loop and visual spatial. The central executive contributed the second largest variance in a regression analysis. Verbal working memory contributed significanly via path analyses (Verbal IQ and the central executive). The phonological loop $r = .370$ and the central executive $r = .517$ exhibited significant correlations, respectively, with mathematics ability (algebra word problem solving ability) ($p < .001$). Taken together, the central executive displayed a predominant contribution to algebraic word performance and verbal working memory played a indirect role via literacy and the central executive's relation to algebraic word problem performance. This suggests that verbal working memory may play a significant role in stoichiometry problem solving given its algebraic word problem character.

A molecule, by its very nature, involves a mathematical expression concerning the proportion of elements present in a bonded state. Further, a reaction between chemicals necessarily involves combining of both whole number and proportion quantities (e.g., stoichiometry). Rules consistent with both mathematical properties and also rules that are specific to the chemistry domain must be used in concert. Thus, both chemistry and mathematical knowledge are needed to think in the chemistry domain.

It is hypothesized that successful chemistry problem performance relies heavily on efficient working memory operations. This claim is grounded in the experimental observation that working memory limitations strongly correlate with deficits in problem solving ability in general and chemistry problem solving ability in particular. What type of working memory operations help tease out differences between successful and unsuccessful chemistry learners and why is it important to consider this question? Given two types of chemistry problems (schematic and verbal) will be investigated it is hypothesized that visuospatial and verbal working memory capacity, respectively, will be crucial to successful chemistry performance.

Student Affect Toward Chemistry Learning and Chemistry Performance

Although there is a wide range of definitions of attitudes, many agree that an attitude is a tendency to think, feel, or act positively or negatively toward objects in our environment (Eagly & Chaiken, 1993, Petty, 1995). Eagly and Chaiken (1993) view attitudes as having three components: the cognitive, the affective, and the behavioral. The cognitive component is a set of beliefs about the attributes of the attitudes' object and its assessment is performed using paper and pencil measures (questionnaires). The affective component includes feelings about the object, and its assessment is performed using psychological indices (heart rate). Finally, the behavioral component refers to the way people react toward the object and its assessment is performed with directly observed behaviors.

In the realm of attitudes in the sciences, Gardner (1975) defined them as a learned predisposition to evaluate in certain ways objects, people, actions, situations, or propositions involved in learning science. Attitudes toward science involve an attitude object such as "science" or "science lessons," "laboratory work" or so on (Schibeci, 1983).

The study of influences of attitudes toward science on science learning in general, and chemistry in particular, have not been extensively studied. The general conclusions of research until 1998, as reviewed by Ramsey (1998), are as follows: Science is considered difficult and not relevant to most peoples' lives, Science is supposed to cause social and environmental problems, Science is more attractive to males than females (with mixed findings emerging from this literature), Interest in science decreases from high school to college, More negative views are associated with the physical sciences than the biological sciences.

Available evidence suggests a low to moderate correlation between attitudes toward science and science achievement (Freedman, 1997; Germann, 1988; Haladyna & Shauhnessy, 1982; Wilson, 1983). From a meta analysis covering literature from 1970 to 1991, for high performing girls doing well and achieving in science was closely linked with liking science (Weinburgh, 1995). The correlation between attitude and achievement in the biological and physical sciences was stronger for females than males, with values ranging from $r = .173$ ($p < .05$) to $r = 359$ ($p < .01$).

The majority of the existing studies address attitudes towards science in general. Only three have studied attitudes toward chemistry in particular (Menis, 1983, 1989; Salta & Tzougraki, 2003). Menis (1983, 1989) found that in an Israeli and British high school sample students' perceived difficulty of chemistry matter correlated with chemistry performance respectively (i.e., $r = .373$ ($p < .01$) and $r = .494$ ($p < .001$). Salta and Tzougraki (2003) made a first attempt to assess chemistry attitudes by developing a scale. Greek high school students served as the sample to evaluate the chemistry attitude scale. The scale was based on the curriculum orientation of Greek secondary science education (high school). A symbolic approach is taken where instruction uses chemical and mathematical symbols and equations to represent the material and to solve algorithmic chemistry problems and exercises.

Thirty questions were given to two pilot and three sample populations of 11^{th} grade Greek high school students. Student chemistry grades at the end of the year were correlated with the four chemistry affect factors. The four factors under consideration were as follows: the importance of chemistry in students lives, perceived difficulty of chemistry material, interest in chemistry, and usefulness of chemistry for student's future careers. Twenty three of the thirty questions significantly loaded onto the four factors. The four factors accounted for 47% of the variance. Reliabilities for the four factors ranged from good to fair: difficulty (Alpha = .87), interest (Alpha = .89), usefulness (Alpha = .71) and importance (Alpha = .67). A multiple regression indicated that difficulty was the most significant predictor of achievement followed by usefulness, and importance. Interest in chemistry was not a significant predictor in this model. No gender differences appeared in the interaction of gender, attitude components, and chemistry performance. Correlations between chemistry attitudes and students' end of year chemistry grades ranged from $r = .17$ ($p < .05$) to $r = .69$ ($p < .001$). To the best of my knowledge, no studies have examined the relation between chemistry attitudes and chemistry performance in U.S University novice undergraduates. One purpose of this study was to examine the relationship between the measures of affect isolated by described by Salta and Tzougraki (2003) and individual differences in chemistry problem solving in U.S. novice undergraduates.

Predictions

The purpose of this thesis is to examine the relations between working memory, chemistry attitudes, and variability in chemistry problem solving in FAU undergraduates. Based on the literature review above, the following predictions seemed warranted:

1. Verbal STM performance and verbal working memory performance will predict performance on algebraic-like chemistry problems (e.g., stoichiometry). This prediction is based on the observation that chemistry is similar to math algebra, and similar relations hold between verbal working memory and algebra.
2. Visuospatial working memory performance will predict performance on geometry-like schematic chemistry problems. This is based on the assumption that schematic chemistry problems require considerable visual working memory to carry out,

3. Chemistry attitudes will predict variability in performance on stoichiometry and schematic chemistry problems and GPA, as found by Salta and Tzougraki (2003).

Method

Participants

139 undergraduate students (91 females, 48 males) at Florida Atlantic University participated in this study for 20 points extra credit in their General Chemistry II class. Age ranged from 18 to 39 years (M = 20.70 years of age). The average grade in the General Chemistry II class that the current sample was drawn from was a C. Grades for General Chemistry I and II lecture are determined according to a median split at 60%. A grade of C is set at 55%. According to this grading scale 40% fail the course and receive a grade of 45% or lower. Without this rather substantial curve, approximately 60% percent of students would receive a grade lower than a C- in General Chemistry courses at FAU.

Measures

Cognitive Tests

Each subject completed a battery of cognitive tests from the Woodcock Johnson III (WJ III) battery. The battery's tests included measures of short-term memory, auditory working memory, picture recognition, spatial relations, visual closure, math fluency and math calculation. Each subject completed the cognitive battery in groups of two to three and were administered the items as outlined in the standardized WJ III examiner's manual.

The following measures were administered to students.

Two measures of verbal working memory, one capacity and one with more central executive involvement, were administered.

1. Auditory Memory Capacity: Digit span- The digit span verbal presentation is a measure of verbal STM capacity. This task comes from the Comprehensive Test of Phonological Processing. In this task a series from two to nine digits were presented one at a time, at a rate of about 3s, by the experimenter. After the series was presented the participant was asked to recall the string of digits, and the task was discontinued after three consecutive failures. There were two practice trials and eight test items.
2. Auditory Working Memory: Auditory working memory measures the central executive using auditory stimuli. It can also be classified as a measure of working memory or divided attention. The participant was asked to listen to a series that contains digits and words, such as "dog, 1, shoe, 8, 2, apple." The participant then attempted to reorder the information, repeating first the objects in sequential order and then the digits in sequential order. This task requires the ability to hold information in immediate awareness, divide the information into two groups, and shift attentional resources to the two new ordered sequences. Auditory working memory has median reliabilities of .92 in the age 5 to 19 range and .94 in the adult range. This is test number 9 of the Woodcock-Johnson III (WJIII) Tests of Cognitive Abilities.

Three measures of visual-spatial working memory, one capacity, and two with predominant central executive involvement were the administered. Both manipulations of visual arrays, visual working memory, and closure of visual arrays were included.

3. Visual Memory Capacity: Picture Recognition: Picture recognition measures visual memory of objects of pictures, an aspect of visual-spatial thinking. The participant's task was to recognize a subset of previously presented pictures within a field of distracting pictures. To eliminate verbal mediation as a memory strategy, varieties of the same type of object were used as the stimuli and distractors for each item (e.g., several different bowls and several different windows). The difficulty of the items increased as the number of pictures in the stimulus set increased. Picture Recognition has median reliabilities of .72 in the age 5 to 19 range and .79 in the adult range. This is test number 13 from the Woodcock-Johnston III (WJIII) Tests of Cognitive Abilities.

4. Visual Working Memory: Spatial Relations: Spatial relations is a test of visual-spatial thinking. This visualization-of-spatial relationships task requires the subject to identify the two or three pieces that form a complete target object. The difficulty increases as the drawings of the pieces are flipped, rotated, and become more similar in appearance. Spatial relations has a median reliability of .81 in the 5 to 19 range and

.93 in the adult range. This is test number 3 of the Woodcock-Johnston III (WJIII) Tests of Cognitive Abilities.

5. Closure Flexibility: Visual closure measures the ability to identify a drawing or picture that is altered in one of several ways. The picture may be distorted, have missing lines or areas, or have a superimposed pattern. This test primarily measures visual processing. This is test number 5 of the Woodcock-Johnston Revised (WJ-R) Test of Cognitive Ability.

Two measures to control for math ability.

5. Calculation: This is test number 5 of the Woodcock-Johnson III Tests of Achievement. Calculation is a test of math achievement that estimates the total number of math procedures mastered by the student. The initial items required the individual to write single numbers. The remaining items required the person to perform addition, subtraction, multiplication, division, and combinations of these basic operations, as well as some geometric, trigonometric, logarithmic, and calculus operations. The calculations involved negative numbers, percents, decimals, fractions, and whole numbers. Calculation has a median reliability of .85 in the 5 to 19 age range and .89 in the adult range.

6. Math fluency: This is test number 10 of the Woodcock-Johnson III Tests of Achievement. Math fluency requires the person to analyze and solve as many math

problems they can during a 5 minute time period. To solve the problems, the person must recognize the procedure to be followed, and then perform relatively simple calculations. Extraneous information in the problem forces the individual to decide the appropriate mathematical operations to use. Item difficulty increases with complex interactions. This test has a median reliability of .92 in the age 5 to 19 range and .95 in the adult range.

Chemistry Test Construction

The purpose of constructing a chemistry and cognitive test battery for General Chemistry students was twofold. First, we wanted to engage in an exploratory correlational study, using a chemistry task analysis, to see how specific outcomes of what students need to learn in General Chemistry II correlate with more general outcomes of attitude, motivation, working memory, and mathematical ability. Second, we wanted to find ways students acquire chemistry knowledge and, more specifically, how cognitive psychology could improve chemistry knowledge in the U.S. This is a major problem, since the majority of General Chemistry II (40%) and Organic Chemistry I and II students (50%) at FAU fail the first time they attempt this course.

To best assess chemistry ability, Dr. Daniel Huchital was sought for help in constructing a chemistry battery. Dr. Hutchital is an expert in Chemistry, and has taught basic and advanced chemistry courses for over 20 years. A chemistry battery was constructed that included algebraic and schematic test items that were deemed typical for

General Chemistry students to encounter at FAU and other Universities. Students taking General Chemistry II were exposed to the topics included in the current test battery in General Chemistry I and General Chemsitry II. Five students had received advanced treatment of some of the battery's contents in Quantitative Chemistry and Organic Chemistry. Test data banks from textbooks, university web materials, and Dr. Huchital's collected test banks were consulted. Eleven algebra-like stoichiometry questions and 19 schematic geometry free-response questions (both with multiple parts) were constructed. Topics of acid/base chemistry, empirical formula determination, percent composition, mixtures, lewis structures, resonance, hybridization, and molecular perspective were included in the chemistry battery. The constructed test was deemed by Dr. Hutchital and five chemistry graduate students to include items of either moderate or high difficulty, and appropriate for differentiating high scoring chemistry students from low scoring chemistry students. To control for possible group effects on chemistry performance, each participant was administered one chemistry question from the group session during the cognitive session. Chemistry performance in small-group administration significantly correlated with chemistry performance in large-group sessions ($r = .85$, $p < .001$).

Chemistry Attitude Questionnaire

A 30-item chemistry attitude scale was administered to each subject. The scale was developed by Salta and Tzougraki (2004) as a measure of chemistry affect. One third of the questions were reversed coded to ensure fidelity of responses. Two versions of the inventory were used (one reverse ordered) to reduce carry-over effects. The subscales for this inventory are perceived difficulty, interest in chemistry, chemistry usefulness and chemistry importance.

Procedure

Each participant was required to attend two testing sessions to receive extra credit in their General Chemistry II class. The first session (the chemistry session) took place on two consecutive Monday evenings. Subjects chose, via email, what session they would attend. During the group sessions subjects were randomly assigned seating; a playing card was placed on each desk top. Participants were paired at the door and each pair was assigned to a seat based on a randomly chosen playing card. 78 and 51 students attended the first and second chemistry sessions, respectively. The chemistry session was held in a 250 capacity lecture hall to mimic conditions of chemistry learning and assessment.

The participants answered questions on personal demographics (i.e., GPA and subject GPA) (see Appendix A), a 30-item chemistry attitude inventory (see Appendix B), 11 algebra-like stoichiometry problems (see Appendix C), 19 schematic geometry problems (see Appendix D), and a 25-question math computation inventory. All tests were in paper and pencil (questionnaire) format. Test section and item order was randomized to create 8 different test versions (see Appendix G). Section and item order were shuffled to minimize carry-over effects. Chemistry graduate students helped determine 1.5 hours as the appropriate amount of time for undergraduates to complete the testing materials.

The second required session entailed a cognitive battery and took a total of one hour to complete. Groups of two to four students were administered tests of digit span, auditory working memory, picture recognition, spatial relations, visual closure, and math fluency (see Appendixes H-N). All tests were administered according to the specification of the Woodcock Johnson III examiner's booklet with one exception: the picture recognition, spatial relations, and visual closure tests were presented by overhead projector, not by individual testing. The Woodcock Johnson III examiner's booklet stimulus pages were photocopied for overhead presentation. Testing took place in Dr. David Bjorklund's lab and in FAU's Behavioral Sciences conference room. At the end of the second session students names were emailed to Dr. Huchital and participants received extra credit in their General Chemistry II classes.

Preliminary Analysis

Data Screening

In total, 30 chemistry problems were solved. Each participant solved 11 free-response algebra-like stoichiometry problems and 19 free-response geometry problems. 139 participants received the stoichiometry and geometry questions in one of six random item and set orders to reduce carry-over effects. Data screening was performed before analysis proceeded. First, univariate descriptive statistics were inspected for accuracy of input. Six out-of-range values were brought closer to the mean because these values were more than 1.5 standard deviations from the mean, and scatterplots clearly showed that these values were outliers. Next, the rarity of missing data did not warrant correction for missing cases (N=3 missing cases). Nonnormal variables were then investigated. Skewness and kurtosis analysis, and their probability plots, revealed they were within reasonable limits. Lastly, variables did not exhibit multicollinearity problems (see Appendix A).

Error Analysis

All chemistry mistakes made by the participants were submitted to error analysis (see Appendix B). A post-doctoral chemistry student and a doctoral chemistry student provided independent ratings for each student's item responses. The grading criteria for participant responses were organized according to conceptual understanding of the material as suggested by the procedures that students chose to use to solve each chemistry problem.

For the stoichiometry questions, scorers rated an item as A (full conceptual understanding), B (conceptual understanding with minor errors, such as mathematical errors), C (indications of some minor conceptual understanding), D (variety of strategies were used in a haphazard or incomplete way), or E (no attempt made). Inter-rater reliability for the two graders was .96. For subsequent data analysis, error categories were recoded as follows: More minor errors were given 2 points and involved combining error categories A and B. These more minor errors were assumed to reflect accurate selection of procedures to solve the problem, but contained an omission error for one subprocedure or a simple calculation error. More major errors involved error category C, and was given 1 point. These errors contained some correct selection of procedures, but most procedures were either omitted or incorrectly selected. Major errors contained either little or no evidence of correct subprocedure selection and execution (categories D and E above), suggesting that students did not possess sufficient understanding to conceptualize the problem.

For the geometry-like schematic chemistry problems, a questionnaire of 19 free-response geometry questions was administered to each subject. The graders were told to grade each subject's responses according to conceptual understanding of the material. For the geometry questions, scores rated an item as A (full conceptual understanding), B (some conceptual understanding with minor errors, such as omission of some subprocedures), C (variety of procedures used in a haphazard or incomplete way), or D (no attempt made). Errors were coded as follows: More minor errors were errors that reflected accurate selection of procedures to solve the problem, but contained an omission error for one subprocedure (2 points). More major errors that contained some correct selection of procedures, but most procedures were either omitted or incorrectly selected (1 point). Major errors contained virtually no correct subprocedures, suggesting that students did not possess sufficient understanding to conceptualize the problem (0 points). Inter-rater reliability for the geometry problems was .93.

Frequencies of stoichiometry error types showed: error type A accounted for 5.25%, error type B accounted for 20.53%, error type C accounted for 13.74%, error type D accounted for 38.78%, and error type E accounted for 21.73% of total error types made (see Appendix A). A Cronbach alpha reliability test helped determine the most appropriate grouping of questions. Grouping error types A and B together yielded Alpha = .7947. Error types C, D, and E were then tested for reliability (Alpha = .7767). These reliability outcomes suggest that error type groupings by conceptual and nonconceptual types were warranted.

Frequencies for the geometry error types: Error type A 29.37%, Error type B 36.13%, Error type C 31.62%, and Error type D 2.88% (see Appendix A). A Cronbach Alpha reliability test was used to help determine the most parsimonious grouping of items. The composite of error types A and B for each item yielded a rationale for grouping the conceptual items together for the analysis (Alpha = .8093). Grouping error types C and D together also supported grouping geometry responses along non conceptual lines (Alpha = .7767).

Overall, the percentages correct on the experimental chemistry tests mirrored the sample class average in General Chemistry I and II, which suggests that the current chemistry battery difficulty level was ecologically valid.

Attitude Scale

A 30-item chemistry attitude scale was administered to each subject. The scale was developed by Salta and Tzougraki (2003) as a measure of chemistry affect. Included latent variables of the inventory are perceived difficulty, interest in chemistry, chemistry usefulness and chemistry importance. These subgroupings were derived from a factor analysis which accounted for 37.2% of the total variance in the construct of *chemistry attitude*. Salta and Tzougraki's (2004) sample derived model had 47% of the total variance captured by the four factors. The dependent variables (23 items) loaded onto the four latent variables.

A subsequent confirmatory factor analysis (CFA) was performed to check the chemistry inventory's fit to the sample being studied. The goodness of fit index was .835 before the analysis began, indicating a moderately acceptable fit between the chemistry construct and the subjects' responses to items in the questionnaire. To increase the goodness of fit between the model and the data, the observed factor loadings were examined. Questions were dropped from further analysis if they exhibited a non-significant loading on their factors. Question 2 "learning chemistry is like Chinese to me" was tossed out of the analysis because of the lack of clarity. No change in goodness of fit was observed. Question 21 "chemistry is like walk-over" was omitted from analysis because its meaning was unclear. The test was constructed by Greek psychologists from three junior and senior high school Greek student samples; problems with translation most likely accounts for the lack of clarity of these questions. Question 20 and 27 were omitted from analysis because they were found to load onto factors that were not consistent with their content. After removing these two items from analysis a goodness of fit index of .863 was achieved. A LM test was then used to eliminate items which loaded onto more than one factor. Item 5, 3, and 23 were subsequently removed from analysis. A .933 goodness of fit index was reached after the analysis was complete. Taken together 7 items were removed from the chemistry affect questionnaire leaving a 16 item chemistry affect scale.

Results and Discussion

Cognitive Measure Correlations

Woodcock Johnson III cognitive sub tests showed predicted relationships (see Appendix C). All significant sub tests relations were positive. Math calculation was positively correlated with math fluency (.436, $p<.01$). Short term memory was positively correlated with working memory (.373, $p<.01$). Picture recognition showed positive correlations with spatial relations (.336, $p<.01$) and visual closure (.201, $p<.05$). Spatial relations and visual closure (.372) exhibited a moderately positive relation ($p<.01$). Math fluency was positively related to working memory (.367, $p<.01$).

Cognitive Factors and Stoichiometry

None of the individual error types by question number showed significant relations with any of the outcome measures (see Appendix C). Conceptual stoichiometry (A/B error types) performance and measures of short-term memory, working memory, picture recognition, spatial relations or visual closure exhibited no significant relations. Math fluency (.289) and math calculation (.359) showed mildly positive correlations with conceptual stoichiometry (both $p<.01$). Mildly significant negative correlations emerged between nonconceptual stoichiometry errors (C/D/E) math calculation (-.312) and math fluency (-.252; both $p<.01$).

Chemistry Affect Relations

The individual affect factors showed strong relations with one another and with overall attitude (see Appendix C). Perceived difficulty showed the following correlations with the other affect subscales: interest in chemistry (.565), chemistry usefulness (.480), chemistry importance (.245) and overall attitude (.419) (all $p<.01$). Interest in chemistry showed the following correlations with the other subscales: chemistry usefulness (.559), chemistry importance (.417) and overall attitude (.903) (all $p<.01$). Finally, chemistry usefulness correlated with chemistry importance (.328) and overall attitude (.711) (both $p<.01$). Chemistry importance showed the following relation: overall attitude (.637) ($p<.01$). These findings suggest that the affect subscales captured separate, though correlated, constructs.

Chemistry Affect Scale and Stoichiometry

Perceived difficulty (.265) and chemistry usefulness (.283) had moderately positive relationships with conceptual stoichiometry (both $p<.01$) (see Appendix C). Conceptual stoichiometry and overall attitude (.210) showed a less significant positive relationship ($p<.05$). No conceptual stoichiometry understanding had a reverse relationship with both perceived difficulty (-.201) and chemistry usefulness (-.176) (both $p<.05$).

Grade Point Average (GPA), Subject GPA (SGPA), and Stoichiometry

GPA and SGPA exhibited the strongest relationships with the predictor (conceptual stoichiometry) and outcome measures (see Appendix C). GPA correlated with conceptual stoichiometry (.389), nonconceptual stoichiometry (-.384) and subject GPA (.576) (all $p<.01$). SGPA correlated with conceptual stoichiometry (.375), nonconceptual stoichiometry (-.370), perceived difficulty (.523), interest in chemistry (.333), chemistry usefulness (.308), and total attitude score (.419) (all $p<.01$). Splitting the conceptual stoichiometry grouping by a 50-50 median split did not affect correlation magnitudes, therefore suggesting that affect was not moderated by overall chemistry ability.

Geometry Questions

None of the geometry questions exhibited consistent significant relations amongst error types (see Appendix C). Conceptual geometry showed the following relationships: GPA (.220), SGPA (.177), math calculation (.206) (all $p<.05$), conceptual stoichiometry (.314) and nonconceptual geometry (-.310) (both $p<.01$). For nonconceptual geometry: GPA (-.220), SGPA (-.177), math calculation (-.206) (all $p<.05$), conceptual stoichiometry (-.314) and nonconceptual stoichiometry (.310) (both $p<.01$).

None of the relations between geometry question type and attitude measure were significant.

Regression Analyses

Two ordinary least-squared multiple regression analyses were performed to examine the relations between conceptual stoichiometry and geometry and the cognitive variables being examined (see Appendix D). First, conceptual stoichiometry was entered as the dependent variable and STM, working memory, picture recognition, spatial relations and closure flexibility as independent variables. None of the variables uniquely contributed to conceptual stoichiometry performance ($R2 = .027$ $p<.613$). A second multiple regression was performed; the mentioned cognitive variables were independent variables and conceptual geometry was the dependent variable. None of the cognitive variables uniquely contributed to conceptual geometry performance ($R2 = .051$, $p<.237$). It is possible that the wrong measures were chosen for assessing chemistry problem solving ability.

An ordinary least-squared multiple regression analysis was then performed with conceptual stoichiometry as the dependent variable and GPA, math calculation, math fluency, and the four subscales of chemistry affect (perçeived difficulty, interest, usefulness, and importance). Regression was used to determine whether relations between predictor variables and chemistry performance were independent or redundant with each other.

In this model three variables independently showed unique predictive power: GPA ($B= 1.879$, $t= 3.972$, $p< .000$), math calculation ($B = .240$, $t = 3.019$, $p< .003$), and usefulness ($B= .236$, $t = 2.318$, $p< .022$). The overall R2 for this model was .309.

In a second step the uniquely significant independent predictors were entered alone into the regression model predicting conceptual stoichiometry performance (GPA, math calculation, and usefulness). This allowed for comparing the predictive validity (in terms of R2) of math fluency, difficulty, interest, and importance with the prior model that included all predictors. In this model, the R2 was .30, which was almost identical to the previous model that included the other non-significant predictors. Thus, these three predictors provided the maximum prediction of variability in algebra-like stoichiometry problems in this investigation. Perceived difficulty, interest, and importance were all redundant with usefulness.

Taken together GPA and math calculation are significant predictors of conceptual stoichiometry performance. The attitude variables (usefulness, difficulty, importance, and interest) predict conceptual stoichiometry beyond mathematical ability (math calculation and math fluency).

These results are somewhat consistent with the Israeli (Menis, 1983), British (Menis, 1989), and Greek (Salta & Tzougraki, 2003) affect studies. In the present study usefulness was an independent predictor of chemistry performance. In the Israeli and British studies difficulty was examined in relation to chemistry performance and the relationship was statistically significant. In the Greek study: difficulty ($B = .297$, $t = 6.688$ ($p < .001$)), usefulness ($B = .174$, $t = 4.075$ ($p < .001$), and importance ($B =.087$, $t = 2.095$ ($p < .05$)). The present study verifies the significant role affect plays in chemistry performance, particularly usefulness.

General Discussion

The purpose of the study was to examine the relations between working memory, chemistry attitudes, and variability in chemistry problem solving in FAU undergraduates. Based on the literature review above, the following predictions seemed warranted:

1. Verbal STM performance and verbal working memory performance would predict performance on algebraic-like chemistry problems (i.e. stoichiometry). This prediction was based on the observation that chemistry is similar to math algebra, and similar relations hold between verbal working memory and algebra.
2. Visuospatial working memory performance would predict performance on geometry-like schematic chemistry problems. This was based on the assumption that schematic chemistry problems require considerable visual working memory to carry out.
3. Chemistry attitudes would predict variability in performance on stoichiometry and schematic chemistry problems and GPA, as found by Salta and Tzougraki (2003).

Robust correlations between GPA (.389) and conceptual stoichiometry and SGPA (.586) (both $p < .01$) and conceptual stoichiometry were observed. The results suggest that something more domain general than just domain specific chemistry knowledge is affecting chemistry knowledge. Regression analyses indicated that SGPA and GPA were unique predictors of conceptual chemistry performance independent of math ability and chemistry affect. GPA and SGPA are measures of overall and subject academic performance, respectively. Since SGPA is specific to chemistry performance, in this study, it is not surprising that SGPA maps strongly onto chemistry performance. A positive correlation between working memory and GPA ($r = .180$, $p<.05$) suggests that working memory may still be a necessary but not sufficient criteria for conceptual chemistry performance. The positively sloped best fit line suggests that at a certain level of conceptual understanding working memory resources play a larger role in chemistry performance (see Appendix E).

Math calculation strongly correlated with conceptual stoichiometry performance ($r = .359$, $p< .01$). The math calculation test is constructed to assess number of executable mathematical operations. According to the reviewed literature, reasoning about chemistry may share overlapping features with reasoning about mathematics. The unique contributions made by math calculation in the multiple regression analyses, when predicting conceptual stoichiometry performance, supports a connection between mathematical reasoning and reasoning about chemical processes

The predictive cognitive variables did not significantly correlate with chemistry performance and were withheld from further analysis. Digit span (verbal STM performance) and auditory working memory did not show significant correlations with either conceptual stoichiometry performance or conceptual geometry performance. Working memory does not appear to be the domain general influence on chemistry ability. In the literature reviewed above no studies have yet (to the best of my knowledge) examined the relationship between chemistry ability and associated cognitive factors. At the early stages of chemistry learning the basic rules and operations (semantics) of the system must be learned. This entails a good deal of memorization and not much insight or discovery learning. Students at this stage most likely rely on rotely memorized exercises; this does not contribute to the generation of solutions to conceptual or novel problems which entail a fair amount of knowledge synthesis. The teaching philosophy of beginner university science courses at many universities nurtures this bottom-up learning approach. After the fundamentals are learned the grammar and logic of chemical processes and reactions allow students to predict chemical structures, chemical pathways, and reaction conditions. Mastered insight and discovery learning are often cultivated. Some students reach this point earlier than others and few have a budding chemical intuition at this stage. The lack of correspondence between measures of STM and auditory working memory and chemistry performance seems parsimonious with the fact that students may not be actively processing and transforming the content at this level of experience with chemistry concepts. A regression analysis supports this observation; no cognitive factors (i.e. STM, auditory working memory, picture recognition, spatial relations, and closure flexibility) uniquely contributed to conceptual stoichiometry performance ($R2 = .027, p<.613$).

To be fair, the tests of working memory may not have been the right ones. The tests may not be tapping the aspects of working memory which are active in novice chemistry performance in a U.S. university. Also, the tests were administered in groups of one to three. The Woodcock Johnson III is standardized for individual testing. The memory tests may have been sensitive to group administration. Chemistry performance was not influenced by group conditions; each participant solved one chemistry item individually. The correlation between group chemistry performance and individual chemistry performance was highly significant ($r = .80$, $p < .001$).

Spatial relations, picture recognition, and visual closure were positively correlated with conceptual geometry performance. At the same time, a standardized regression analysis indicated that visuospatial assessments did not uniquely contribute to conceptual geometry performance ($R^2 = .051$, $p < .237$). The small range and high cognitive battery scores (see table 1) may help explain the small explanatory power. For each cognitive test, participants scored at a very high percentile (see Appendix A). The lack of between participant variation in performance on the included cognitive battery may have suppressed relations between cognitive measures and chemistry outcomes.

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Appendix A: Descriptives and Overall Frequency Error Type Tables

Table A1.
Descriptives for cognitive, attitude components, and conceptual groupings.

	N	Minimum	Maximum	Mean	SD
GPA	132	2	4	3.24673	0.454505
Subject GPA (SGPA)	137	1	4	2.87	0.745
Math Calculation	138	31	44	38.55	2.813
Short Term Memory	134	6	9	8.7313	0.5902
Working Memory	134	2	37	26.5522	6.14434
Picure Recognition	134	6	56	45.194	7.29556
Spatial Closure	134	41	77	65.1716	6.32042
Closure Flexibility	134	27	42	36.0373	2.95431
Conceptual Stoichiometry	139	0	10	2.8345	2.57805
Nonconceptual Stoichiometry	139	1	11	8.1655	2.58366
Conceptual Geometry	139	0	17	11.964	3.82859
Nonconceptual Geometry	139	2	19	7.036	3.82859
Attitude Total	138	48	127	95.1449	16.47274
Perceived Difficulty	137	8	28	18.2774	4.20037
Interest in Chemistry	137	10	41	27.3066	7.02052
Chemistry Usefulness	137	3	15	9.365	2.49964
Chemistry Importance	137	5	25	17.8832	4.04763

Table A2.
Summary of Percent Frequencies of Error Type by Stoichiometry and Geometry Problems (averaged across all chemistry problems).

Question Type	Error Type	Percent Frequency
Stoichiometry	A	5.25
Stoichiometry	B	20.53
Stoichiometry	C	13.74
Stoichiometry	D	38.78
Stoichiometry	E	21.73
Geometry	A	29.37
Geometry	B	36.13
Geometry	C	31.62
Geometry	D	2.88

For the stoichiometry questions, scorers rated an item as A (full conceptual understanding), B (conceptual understanding with minor errors, such as mathematical errors), C (indications of some minor conceptual understanding), D (variety of strategies were used in a haphazard or incomplete way), or E (no attempt made).

For the geometry questions, scores rated an item as A (full conceptual understanding), B (some conceptual understanding with minor errors, such as omission of some subprocedures), C (variety of procedures used in a haphazard or incomplete way), or D (no attempt made).

Appendix B: Error type analysis for each problem

Table B1.
Descriptives for Error Type for each Individual Stoichiometry Problem.

Error Type	N	Mean	SD	Minimum	Maximum
Error A for Stoichiometry 1A	139	0.0288	0.16778	0	1
Error B for Stoichiometry 1A	139	0.2158	0.41288	0	1
Error C for Stoichiometry 1A	139	0.2734	0.44731	0	1
Error D for Stoichiometry 1A	139	0.3381	0.47478	0	1
Error E for Stoichiometry 1A	139	0.1439	0.35224	0	1
Error A for Stoichiometry 1B	139	0.0072	0.08482	0	1
Error B for Stoichiometry 1B	139	0.0719	0.25933	0	1
Error C for Stoichiometry 1B	139	0.0863	0.28187	0	1
Error D for Stoichiometry 1B	139	0.4604	0.50023	0	1
Error E for Stoichiometry 1B	139	0.3741	0.48564	0	1
Error A for Stoiciometry 2A	139	0.0288	0.16778	0	1
Error B for Stoichiometty	139	0.5468	0.49961	0	1
Error C for Stoichiometry 2A	139	0.1007	0.30205	0	1
Error D for Stoichiometry 2A	139	0.2302	0.42249	0	1
Error E for Stoichiometry 2A	139	0.0935	0.29222	0	1
Error A for Stoichiometry 2B	139	0.0576	0.23374	0	1
Error B for Stoichiometry 2B	139	0.1295	0.33696	0	1
Error C for Stoichiometry 2B	139	0.1007	0.30205	0	1
Error D for Stoichiometry 2B	139	0.446	0.49888	0	1
Error E for Stoichiometry 2B	139	0.2662	0.44356	0	1
Error A for Stoichiometry 2C	139	0.0935	0.29222	0	1
Error B for Stoichiometry 2C	139	0.1655	0.37295	0	1
Error C for Stoichiometry 2C	139	0.1151	0.32031	0	1
Error D for Stoichiometry 2C	139	0.3381	0.47478	0	1
Error E for Stoichiometry 2C	139	0.2806	0.45091	0	1
Error A for Stoichiometry 3A	139	0.0288	0.16778	0	1
Error B for Stoichiometry 3A	139	0.1942	0.39705	0	1
Error C for Stoichiometry 3A	139	0.1007	0.30205	0	1
Error D for Stoichiometry 3A	139	0.5971	0.49225	0	1
Error E for Stoichiometry 3A	139	0.0791	0.27093	0	1
Error A for Stoichiometry 3B	139	0.0288	0.16778	0	1
Error B for Stoichiometry 3B	139	0.1727	0.37932	0	1
Error C for Stoichiometry 3B	139	0.0791	0.27093	0	1
Error D for Stoichiometry 3B	139	0.4029	0.49225	0	1
Error E for Stoichiometry 3B	139	0.3165	0.46681	0	1
Error A for Stoichiometry 4A	139	0.1367	0.34476	0	1
Error B for Stoichiometry 4A	139	0.223	0.41778	0	1
Error C for Stoichiometry 4A	139	0.0288	0.16778	0	1
Error D for Stoichiometry 4A	139	0.5108	0.50169	0	1

Error E for Stoichiometry 4A	139	0.1007	0.30205	0	1
Error A for Stoichiometry 4B	139	0.0432	0.20396	0	1
Error B for Stoichiometry 4B	139	0.1655	0.37295	0	1
Error C for Stoichiometry 4B	139	0.1367	0.34476	0	1
Error D for Stoichiometry 4B	139	0.3525	0.47948	0	1
Error E for Stoichiometry 4B	139	0.3022	0.46085	0	1
Error A for Stoichiometry 4C	139	0.0144	0.11952	0	1
Error B for Stoichiometry 4C	139	0.1439	0.35223	0	1

Table 1 (continued).
Descriptives for Error Type by Stoichiometry Problem.

Stoichiomety Error Type	N	Mean	SD	Minimum	Maximum
Error C for Stoichiometry 4C	139	0.2158	0.41288	0	1
Error D for Stoichiometry 4C	139	0.3669	0.4837	0	1
Error E for Stoichiometry 4C	139	0.259	0.43967	0	1
Error A for Stoichiometry 5	139	0.3633	0.47722	0	1
Error B for Stoichiometry 5	139	0.225	0.42333	0	1
Error C for Stoichiometry 5	139	0.1572	0.35543	0	1
Error D for Stoichiometry 5	139	0.1776	0.38811	0	1
Error E for Stoichiometry 5	139	0.0823	0.27132	0	1

Table B2.
Frequency of Error Type by Stoichiometry Problem

Stoichiometry Error Type	Frequency	Percent
Error A for Stoichiometry 1A	4	2.9
Error B for Stoichiometry 1A	30	21.6
Error C for Stoichiometry 1A	38	27.3
Error D for Stoichiometry 1A	47	33.8
Error E for Stoichiometry 1A	20	14.4
Error A for Stoichiometry 1B	1	0.7
Error B for Stoichiometry 1B	10	7.2
Error C for Stoichiometry 1B	12	8.6
Error D for Stoichiometry 1B	64	46
Error E for Stoichiometry 1B	52	37.4
Error A for Stoiciometry 2A	4	2.9
Error B for Stoichiometry 2A	76	54.7
Error C for Stoichiometry 2A	14	10.1
Error D for Stoichiometry 2A	32	23
Error E for Stoichiometry 2A	13	9.4
Error A for Stoichiometry 2B	8	5.8
Error B for Stoichiometry 2B	18	12.9
Error C for Stoichiometry 2B	14	10.1
Error D for Stoichiometry 2B	62	44.6
Error E for Stoichiometry 2B	37	26.6
Error A for Stoichiometry 2C	13	9.4
Error B for Stoichiometry 2C	23	16.5
Error C for Stoichiometry 2C	16	11.5
Error D for Stoichiometry 2C	47	33.8
Error E for Stoichiometry 2C	39	28.1
Error A for Stoichiometry 3A	4	2.9
Error B for Stoichiometry 3A	27	19.4
Error C for Stoichiometry 3A	14	10.1
Error D for Stoichiometry 3A	83	59.7
Error E for Stoichiometry 3A	11	7.9
Error A for Stoichiometry 3B	4	2.9
Error B for Stoichiometry 3B	24	17.3
Error C for Stoichiometry 3B	11	7.9
Error D for Stoichiometry 3B	56	40.3
Error E for Stoichiometry 3B	44	31.7
Error A for Stoichiometry 4A	19	13.7
Error B for Stoichiometry 4A	31	22.3
Error C for Stoichiometry 4A	4	2.9
Error D for Stoichiometry 4A	71	51.1
Error E for Stoichiometry 4A	14	10.1
Error A for Stoichiometry 4B	6	4.3

Error B for Stoichiometry 4B	23	16.5
Error C for Stoichiometry 4B	19	13.7
Error D for Stoichiometry 4B	49	35.3
Error E for Stoichiometry 4B	42	30.2
Error A for Stoichiometry 4C	2	1.4
Error B for Stoichiometry 4C	20	14.4

Table B2 (continued).

Frequency of Error Type by Stoichiometry Question.

Stoichiometry Error Type	Frequency	Percent
Error C for Stoichiometry 4C	30	21.6
Error D for Stoichiometry 4C	51	36.7
Error E for Stoichiometry 4C	36	25.9
Error A for Stoichiometry 5	15	10.8
Error B for Stoichiometry 5	32	23
Error C for Stoichiometry 5	38	27.3
Error D for Stoichiometry 5	31	22.3
Error E for Stoichiometry 5	24	17.3

Table B3.
Descriptives of Error Type by Geometry Question

Geometry Error Type	Mean	SD	Minimum	Maximum
Error A for Geo 1A	0.1942	0.39705	0	1
Error B for Geo 1A	0.2014	0.40253	0	1
Error C for Geo 1A	0.5755	0.49605	0	1
Error D for Geo 1A	0.0288	0.16778	0	1
Error A for Geo 1B	0.5612	0.49804	0	1
Error B for Geo 1B	0.2158	0.41288	0	1
Error C for Geo 1B	0.1942	0.39705	0	1
Error D for Geo 1B	0.0288	0.16778	0	1
Error A for Geo 1C	0.0144	0.39705	0	1
Error B for Geo 1C	0.0288	0.16778	0	1
Error C for Geo 1C	0.0144	0.11952	0	1
Error D for Geo 1C	0.0791	0.27093	0	1
Error A for Geo 1D	0.8633	0.34476	0	1
Error B for Geo 1D	0.0432	0.20396	0	1
Error C for Geo 1D	0.0216	0.14584	0	1
Error D for Geo 1D	0.0504	0.21948	0	1
Error A for Geo 1E	0.8777	0.32882	0	1
Error B for Geo 1E	0.1942	0.39705	0	1
Error C for Geo 1E	0.0432	0.20396	0	1
Error D for Geo 1E	0.6475	0.47978	0	1
Error A for Geo 1F	0.2086	0.4078	0	1
Error B for Geo 1F	0.0935	0.29222	0	1
Error C of Geo 1F	0.0504	0.21948	0	1
Error D for Geo 1F	0.5252	0.50117	0	1
Error A for Geo 1G	0.2302	0.42249	0	1
Error B for Geo 1G	0.1942	0.39705	0	1
Error C for Geo 1G	0.0504	0.21948	0	1
Error D for Geo 1G	0.5612	0.49804	0	1
Error A for Geo 1H	0.1439	0.35224	0	1
Error B for Geo 1H	0.2302	0.42249	0	1
Error C for Geo 1H	0.0647	0.24697	0	1
Error D for Geo 1H	0.1942	0.39705	0	1
Error A for Geo 1I	0.2374	0.42703	0	1
Error B for Geo 1I	0.1151	0.32031	0	1
Error C for Geo 1I	0.0791	0.27093	0	1
Error D for Geo 1I	0.7266	0.44731	0	1
Error A for Geo 1J	0.1439	0.35224	0	1
Error B for Geo 1J	0.0504	0.21948	0	1

Error C for Geo 1J	0.1942	0.39705	0	1
Error D for Geo 1J	0.5899	0.49363	0	1
Error A for Geo 1K	0.1583	0.36632	0	1
Error B for Geo 1K	0.0576	0.23374	0	1
Error C for Geo 1K	0.0072	0.08482	0	1
Error D for Geo 1K	0.7554	0.43141	0	1

Table B3 (continued).

Desriptives for Error Type by Geometry Problem.

Error Type	Mean	SD	Minimum	Maximum
Error A for Geo 2A	0.1439	0.35224	0	1
Error B for Geo 2A	0.0935	0.29222	0	1
Error C for Geo 2A	0.0504	0.29222	0	1
Error C for Geo 2A	0.5396	0.50023	0	1
Error D for Geo 2A	0.2878	0.45436	0	1
Error A for Geo 2B	0.1223	0.32882	0	1
Error B for Geo 2B	0.7914	0.4078	0	1
Error C for Geo 2B	0.0576	0.23374	0	1
Error D for Geo 2B	0.1151	0.32031	0	1
Error A for Geo 2C	0.036	0.18689	0	1
Error B for Geo 2C	0.2806	0.45091	0	1
Error C for Geo 2C	0.3741	0.48564	0	1
Error D for Geo 2C	0.3022	0.46085	0	1
Error A for Geo 2D	0.1079	0.31139	0	1
Error B for Geo 2D	0.2158	0.43562	0	1
Error C for Geo 2D	0.6043	0.49077	0	1
Error D for Geo 2D	0.036	0.18689	0	1
Error A for Geo 3A	0.1079	0.31139	0	1
Error B for Geo 3A	0.3165	0.46681	0	1
Error C for Geo 3A	0.5252	0.50117	0	1
Error D for Geo 3A	0.0504	0.21948	0	1
Error A for Geo 3B	0.8633	0.34476	0	1
Error B for Geo 3B	0.0432	0.20396	0	1
Error C for Geo 3B	0.0216	0.14584	0	1
Error D for Geo 3B	0.0504	0.21948	0	1
Error A for Geo 3C	0.8777	0.32882	0	1
Error B for Geo 3C	0.1942	0.39705	0	1
Error C for Geo 3C	0.0432	0.20396	0	1
Error D for Geo 3C	0.6475	0.47978	0	1
Error A for Geo 3D	0.2086	0.4078	0	1
Error B for Geo 3D	0.0935	0.29222	0	1
Error C for Geo 3D	0.1942	0.39705	0	1
Error D for Geo 3D	0.2014	0.40253	0	1

Table B4.
Frequencies of Error Type by Geometry Question

Geometry Error Type	Frequency	Percent
Error A for Geo 1A	27	19.4
Error B for Geo 1A	28	20.1
Error C for Geo 1A	80	57.6
Error D for Geo 1A	4	2.9
Error A for Geo 1B	78	56.1
Error B for Geo 1B	30	21.6
Error C for Geo 1B	27	19.4
Error D for Geo 1B	4	2.9
Error A for Geo 1C	2	1.4
Error B for Geo 1C	11	7.9
Error C for Geo 1C	120	86.3
Error D for Geo 1C	6	4.3
Error A for Geo 1G	3	2.2
Error B for Geo 1D	7	5
Error C for Geo 1D	122	87.8
Error D for Geo 1D	7	5
Error A for Geo 1E	93	66.9
Error B for Geo 1E	30	21.6
Error C for Geo 1E	13	9.4
Error D for Geo 1E	3	2.27
Error A for Geo 1F	79	56.8
Error B for Geo 1F	30	21.6
Error C of Geo 1F	24	17.3
Error D for Geo 1F	6	4.3
Error A for Geo 1G	17	12.2
Error B for Geo 1G	89	64
Error C for Geo 1G	27	19.4
Error D for Geo 1G	6	4.3
Error A for Geo 1H	90	64.7
Error B for Geo 1H	29	20.9
Error C for Geo 1H	13	9.4
Error D for Geo 1H	7	5
Error A for Geo 1I	73	52.5
Error B for Geo 1I	32	23
Error C for Geo 1I	27	19.4
Error D for Geo 1I	7	5
Error A for Geo 1J	78	56.1
Error B for Geo 1J	20	14.4

Error C for Geo 1J	32	23
Error D for Geo 1J	9	6.5
Error A for Geo 1K	27	19.4
Error B for Geo 1K	63	45.3
Error C for Geo 1K	33	23.7
Error D for Geo 1K	16	11.5

Table B4 (continued).
Frequency of Error Type by Geometry Question.

Geometry Error Type	Frequency	Percent
Error A for Geo 2A	11	7.9
Error B for Geo 2A	101	72.7
Error C for Geo 2A	20	14.4
Error C for Geo 2A	7	5
Error D for Geo 2A	27	19.4
Error A for Geo 2B	82	59
Error B for Geo 2B	22	15.8
Error C for Geo 2B	8	5.8
Error D for Geo 2B	1	0.7
Error A for Geo 2C	105	75.7
Error B for Geo 2C	20	14.4
Error C for Geo 2C	13	9.4
Error D for Geo 2C	7	5
Error A for Geo 2D	75	54
Error B for Geo 2D	40	28.8
Error C for Geo 2D	17	12.2
Error D for Geo 2D	110	79.1
Error A for Geo 3A	8	5.8
Error B for Geo 3A	16	11.5
Error C for Geo 3A	5	3.6
Error D for Geo 3A	39	28.1
Error A for Geo 3B	52	37.4
Error B for Geo 3B	42	30.2
Error C for Geo 3B	6	4.3
Error D for Geo 3B	15	10.8
Error A for Geo 3C	35	25.2
Error B for Geo 3C	84	60.4
Error C for Geo 3C	5	3.6
Error D for Geo 3C	15	10.8
Error A for Geo 3D	44	31.7
Error B for Geo 3D	73	52.5
Error C for Geo 3D	7	5
Error D for Geo 3D	9	6.2

Appendix C: Correlation Matrix

Table C1a

	GPA	SGPA	STM	WM	Picture	Spatial	Closure	Fluency
GPA	1	.576**	.198*	.180*	0.008	0.149	0.025	.308**
SGPA	.576**	1	0.097	0.168	0.106	.302**	0.034	.179*
math calc]	.182*	0.157	-0.04	0.114	0.145	0.048	0.067	.436**
STM	.198*	0.097	1	.373**	-0.075	-0.072	-0.093	0.136
WM	.180*	0.168	.373**	1	0.024	.182*	0.124	.367**
Picture	0.008	0.106	-0.075	0.024	1	.336**	.201*	0.135
Spatial	0.149	.302**	-0.072	.182*	.336**	1	.372**	0.09
Closure	0.025	0.034	-0.093	0.124	.201*	.372**	1	0.116
Fluency	.308**	.179*	0.136	.367**	0.135	0.09	0.116	1
Difficulty	.310**	.523**	0.037	0.003	-0.051	0.099	-0.053	0.151
Interest	0.088	.333**	0.011	.373**	-0.075	-0.072	-0.093	0.136
Usefulness	0.034	.308**	0.064	0.07	0.004	0.025	-0.003	0.145
Importance	-0.005	0.115	-0.093	0.01	0.047	0.14	-0.037	0.09
Attitude Total	0.143	.419**	0.001	-0.009	-0.053	0.043	-0.094	0.077

** $p < .01$
*$p < .05$

- Significant correlations are left indented

Table C1a
Correlation Matrix

	Conceptual Stoic	Nonconceptual Stoic	Conceptual Geo	Nonconcept Geo	Math Calc
GPA	.389**	.384**-	.220*	.220*-	.182*
SGPA	.375**	.370**-	.177*	.177*-	0.157
math calc]	.359**	.364**-	.206*	.206*-	1
STM	-0.07	0.07	-0.046	0.046	-0.04
WM	0.111	-0.112	-0.117	0.117	0.114
Picture	0.033	-0.035	0.158	-0.158	0.145
Spatial	0.045	-0.043	0.105	-0.105	0.048
Closure	0.034	-0.035	-0.051	0.051	0.067
Fluency	.289**	.289**-	0.12	-0.12	.436**
Difficulty	.855**	.853**-	0.137	-0.137	.212*
Interest	0.101	-0.097	0.05	-0.05	0.064
Usefulness	.283**	.275**-	0.163	-0.163	.190*
Importance	0.135	-0.133	0.159	-0.159	0.096
Attitude Total	.222**	.218*-	0.143	-143	0.159

** *p*< .01
**p*<.05

- Significant correlations are left indented.

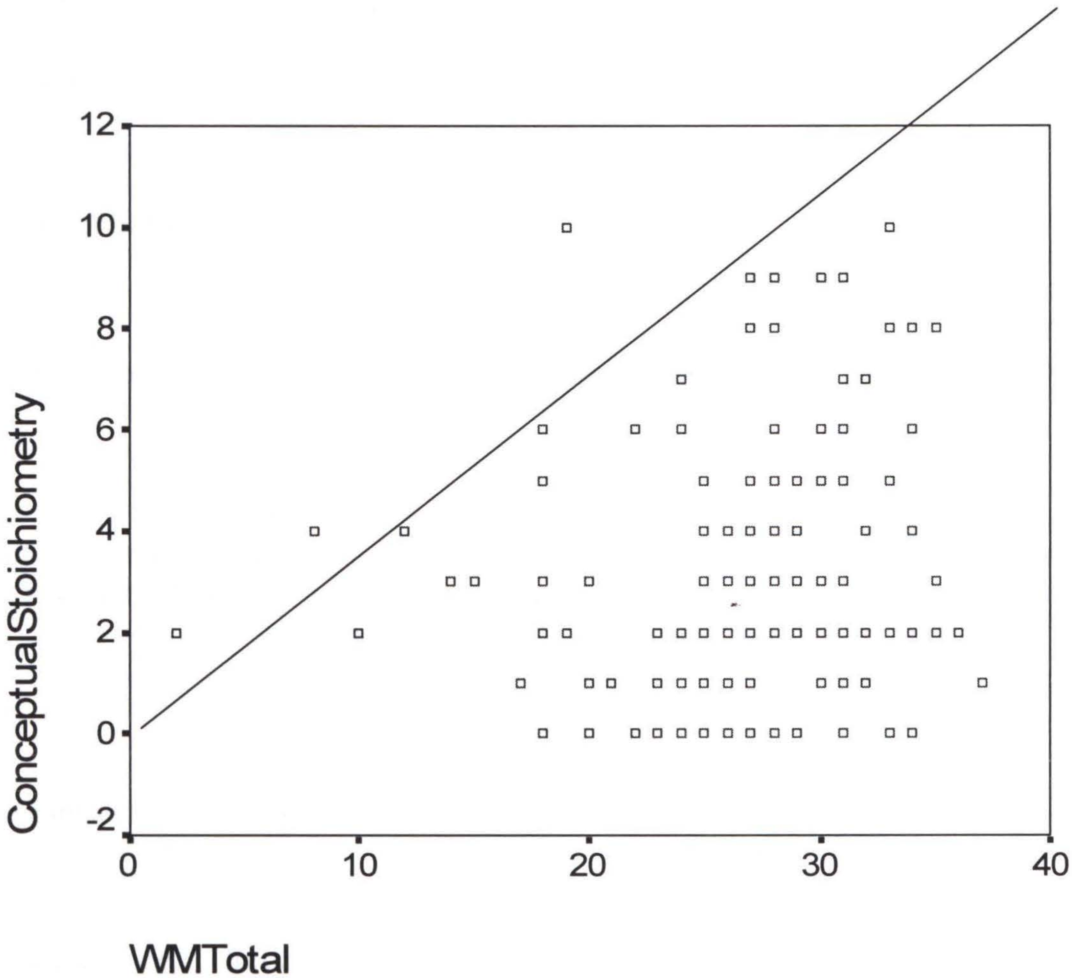
Appendix D: Regression Table

Table D:
Regression Table

Model	Beta	t	Sig.	R2 = .309
Constant		-5.16	0	
Fluency	0.034	0.375	0.708	
GPA	0.337	3.972	0	
Math calc	0.234	2.318	0.022	
Usefulness	0.262	3.019	0.003	
Difficulty	-0.008	-0.073	0.942	
Interest	-0.083	-0.738	0.462	
Importance	0.101	1.185	0.239	

* DV is conceptual stoichiometry

Appendix E: <u>Conceptual stocihiometry performance as a function of working memory performance.</u>



Appendix F: Demographic Questionnaire

Please answer the following questions in an honest and brief manner

Your Name:

Your date of birth:

Is the course that you are getting extra credit for Dr. Huchital's class? If not what course?

Reason why taking Huchital's class (I.E. premed, distribution requirement, interest, major requirement, etc.):

College major:

Class (Ciricle one): freshman sohmore junior senior other

Overall GPA:

Chemistry courses taken and grades for each course:

Gender

Languages spoken:

Appendix G: Chemistry Attitude and Motivation Questionnaire.

INSTRUCTIONS: Please circle how strongly you agree or disagree with each of the following by circling the appropriate number.

1. = strongly unfavorable to the concept
2. = somewhat unfavorable to the concept
3. = undecided
4. = somewhat favorable to concept
5. = strongly favorable to the concept

---

1. I like this chemistry course more than others.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

2. Chemical symbols are like Chinese to me.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

3. I would like to have chemistry lessons more often.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

4. The progress of chemistry is responsible for many environmental problems.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

5. Chemistry knowledge is useful to interpret many aspects of our everyday lives

1	2	3	4	5
strongly unfavorable				strongly favorable

---

6. This chemistry course is not related to the other courses I take (have taken).

1	2	3	4	5
strongly unfavorable				strongly favorable

---

7. I solve chemistry exercises very easily.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

8. Chemistry courses help the development of my conceptual skills.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

9. During chemistry lessons, I am bored.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

10. Chemistry knowledge will be useless after my graduation.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

11. Chemistry knowledge is essential for the understanding of other courses.

1 strongly unfavorable	2	3	4	5 strongly favorable

12. The progress of chemistry improves the quality of our lives.

1 strongly unfavorable	2	3	4	5 strongly favorable

13. Chemistry is our hope for solving many environmental problems.

1 strongly unfavorable	2	3	4	5 strongly favorable

14. My future career is independent from chemistry knowledge.

1 strongly unfavorable	2	3	4	5 strongly favorable

15. The progress of chemistry contributes to the development of country.

1 strongly unfavorable	2	3	4	5 strongly favorable

16. Chemistry is a very sophisticated subject for our compulsory education.

1	2	3	4	5
strongly unfavorable				strongly favorable

17. I make many efforts to understand chemistry.

1	2	3	4	5
strongly unfavorable				strongly favorable

18. I find the use of chemical symbols easy.

1	2	3	4	5
strongly unfavorable				strongly favorable

19. The profession of a chemist is one of the less attractive.

1	2	3	4	5
strongly unfavorable				strongly favorable

20. Every citizen must have chemistry knowledge.

1	2	3	4	5
strongly unfavorable				strongly favorable

21. I hate chemistry courses.

1	2	3	4	5
strongly unfavorable				strongly favorable

22. Chemistry knowledge is necessary for my future career.

1 strongly unfavorable	2	3	4	5 strongly favorable

23. I would like to have fewer chemistry lessons.

1 strongly unfavorable	2	3	4	5 strongly favorable

24. I understand the chemistry concepts very easily.

1 strongly unfavorable	2	3	4	5 strongly favorable

25. I find the chemistry course very interesting.

1 strongly unfavorable	2	3	4	5 strongly favorable

26. When I try to solve chemistry exercises, my mind goes blank.

1 strongly unfavorable	2	3	4	5 strongly favorable

27. People are indifferent to chemistry applications.

1 strongly unfavorable	2	3	4	5 strongly favorable

28. The progress of chemistry worsens the conditions of living.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

29. I am incapable of interpreting the world around me using chemistry knowledge.

1	2	3	4	5
strongly unfavorable				strongly favorable

---

30. I would like to become a chemist when I finish school.

1	2	3	4	5
strongly unfavorable				strongly favorabl

Appendix H: <u>Item Factor Clustering for Attitude Questionnaire</u>

"Perceived difficulty of chemistry" (items 7, 24, 17, 18, 26, 2)
"Interest in chemistry" (items 23, 21, 9, 25, 10, 3, 19, 1, and 16)
"Usefulness of chemistry for student's future career" (items 22, 30, and 14)
"Importance of chemistry for student's life" (items 12, 13, 15, 5, and 20)

Appendix I: Instructions for Stoichiometry and Geometry Chemistry Tests

Directions: Concepts tested include General Chemistry II material. Please try your best. If you get to a question that you cannot solve, just give your best guess. Please remember that my masters thesis will only be successful if you give your best effort. I really appreciate you spending time via this project, which aims to understand how people learn chemistry.

Appendix J: Stoichiometry Chemistry Test (5 questions with multiple components)

1.

An unknown compound consists of only carbon, hydrogen, ***and oxygen***.

a) When 5.467 grams of this compound are burned, 15.02 grams of carbon dioxide and 2.458 grams of water are burned and the result indicates 1.02 g carbon and 2.03 g hydrogen are present in the compound. Determine the empirical formula of unknown compound.

b) Other experiments suggest that the compound has a molar mass somewhere **betweeen** 230 – 260 g/mol. Calculate the **true** molar mass of the unknown

2.

The following two solutions are mixed together:

60.0 mL of 0.150-molar sodium carbonate
1110.0 mL of 0.200-molar siver nitrate

A precipitate of silver carbonate is formed in a double displacement reaction.

a) Write a **complete, balanced molecular** equation, and then a **net ionic** equation for this chemical reaction. (Please include state symbols such as (s), (l), etc).

b) Calculate the mass of silver carbonate which would be formed, assuming the reaction goes to completion.

c) If 13.2 g of silver carbonate were collected what would be the percent yield you would report?

3.

Phthalic acid ($C_6H_4(COOH)_2$) is a colorless white solid; it is a **diprotic** acid.

a) Write a complete molecular, balanced equation for the neutralization of phthalic acid with sodium hydroxide

b) A sample of phthalic acid was dissolved in 10 mL water and titrated against 0.500 –molar NaOH. It takes a total of 14.7 mL of base to completely neutralize both acids. Determine the molar mass of the phthalic acid sample in the solution being titrated.

4.

Limonite, an ore of iron, is brought into solution in an acidic medium and titrated with $KMnO_4$.

a) What is the oxidation number of Mn in $KMnO_4^{-}$?

b) Balance the following molecular equation:

$MnO_4^{-}\ (aq) + Fe^{2+}\ (aq) \Rightarrow Fe^{3+}\ (aq) + Mn^{2+}\ (aq)$

c) It is found that a 1.000-g sample of the ore requires 75.52 mL of 0.0205 M $KMnO_4$. What is the percent of Fe in the sample.

5.

A solution is prepared by dissolving x grams of potassium nitrate in water and diluting it to a total volume of ***100.0 mL***. Another solution is prepared by dissolving y grams of sodium chloride in water and diluting it to a total volume of 500.0 mL. Both solutions are ***then mixed together***, giving a final concentration of KNO_3 of ***0.073 M*** and a final concentration of NaCl of ***0.128 M***. Calculate x and y.

Appendix K: Geometry Chemistry Problems (3 questions with multiple components)

1.

For each of the following molecules, please draw the best possible ***Lewis structure*** and predict the ***electronic and molecular geometry***. Please indicate **resonance** where appropriate.

HCN **SCl_2**

HNO_3 **$HClO_2$**

BF_3 **ClF_3**

For each of the following molecules, please draw the best possible ***Lewis structure*** and predict the ***electronic and molecular geometry***. Please indicate **resonance** where appropriate.

SO_2

SeF_4

XeF_2

$AsCl_5$

AsF_6^-

2.

For each of the following ions, draw **the best possible Lewis structure**. On the basis of that Lewis structure, predict the ***electron-pair geometry***, the ***molecular geometry*** and the ***hybridization of the central atom***:

IF_4^- **PCl_4^+**

SeO_3^{2-} **I_3^-**

3.

Consider the four molecules OF_2 , COF_2 , SOF_2 and $XeOF_2$, each of which has one central atom (O, C, S, and Xe, respectively).

For each of these molecules, provide the ***best possible Lewis structure*** determined using formal charge reasoning. Then provide your best ***perspective drawing of the molecular geometry***, including lone pairs on the central atom. (You may wish to provide a ***description of the molecular geometry if your drawing seems ambiguous***.)

Lewis structure: Perspective of the molecule:

OF_2

COF_2

Lewis structure: Perspective of the molecule:

SOF_2

$XeOF_2$

Appendix L: <u>Order of items and tests admnistered</u>

		Order of Items Within Each Task (Except Math)	Reverse Order
		A	B
Order of The Tests Administered	1	Verbal Visual Attitude Math	Verbal Visual Attitude Math
	2	Math Attitude Visual Verbal	Math Attitude Visual Verbal
	3	Visual Attitude Math Verbal	Visual Attitude Math Verbal
	4	Verbal Math Attitude Visual	Verbal Math Attitude Visual
	5	Math Visual Verbal Attitude	Math Visual Verbal Attitude

Appendix M: Instructions for the digit span test (short-term memory)

I will now say some numbers one at a time. I want you to wait until I say the last number and then recall the numbers. Just write down the numbers that you heard in the order that you heard them. For example, if I say 2, 8, 4 then you would write down 2, 8, 4 in the space provided. Let's try some for practice.

Appendix N: Instructions for the auditory working memory task

This is a test of auditory memory span. I am going to name some things like animals or foods, and some numbers. After I say them, you write down the things in the same order that I said them. Then you write down the numbers in the same order that I said them. For example, if I say "chair, 1, table" then you would write down "chair, table, 1." The series will begin with one number and one thing and will become progressively larger in numbers and things.

Appendix O: Instructions for picture recognition task

You will now be presented with a series of pictures. After examining the picture you will circle which, of a series of pictures, you have seen. Circle the letters of the pictures you have seen. The pictures appear on the transparency for 5 seconds each, so don't get caught on a particular picture. Let's try some for practice.

Appendix P: Instructions for the spatial relations task

The visualization-of-spatial relationships task requires you to identify two or three pieces to form a complete target shape. Please circle the letters that correspond to picture pieces, which compose the target shape. The difficulty increases as the drawings of the pictures are flipped, rotated, or become more similar to one another in appearance. Here are some practice items. Just try your best.

Appendix Q: Instructions for visual closure task

I am going to show you a series of pictures and I want you to write down what pictures you see. Let's try two for practice.

Appendix R: Instructions for the math calculation task

The following questions assess your ability to do a wide variety of mathematical operations, from basic arithmetic to algebra to calculus. Don't worry if you don't know how to solve a problem, give it your best guess. *Please ignore* the two blank boxes in the upper left corner of the page.

Appendix S: Instructions for math fluency task

This next subtest assesses the speed that you can solve basic arithmetic problems. Just solve as many problems as you can. Start at the upper-left hand side and continue across. Then continue to the next line, and so on...Be sure you go to the next page. Just answer the problems as fast and accurately as you can. I will ask you to stop after exactly 3 minutes.