An Assessment of Conceptual Understanding of Metabolic Pathways

Amani Atiyalla Abdugadar

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AN ASSESSMENT OF CONCEPTUAL UNDERSTANDING
OF METABOLIC PATHWAYS

A Dissertation Submitted in Partial Fulfillment
of the Requirements for the Degree of
Doctor of Philosophy

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ABSTRACT


Researchers have previously studied misconceptions of biochemistry topics such as photosynthesis, protein structure, and ATP-production. However, no studies have reported on students’ misconceptions regarding major metabolic pathways. Since learning metabolism builds on students’ prior knowledge, new material being learned will be affected by the presence of any misconceptions. Some of these misconceptions will be robust and thus hard to be replaced by the correct concepts. Thus, if students are to learn new material, these misconceptions must be diminished. This dissertation focused on the origins of these misconceptions, investigated what misconceptions students had on metabolism, and why students developed misconceptions instead of proper scientific conceptions. The ultimate goal of this study was to help students improve their conceptual understanding of general chemistry concepts that impact metabolic pathways by developing a video that targeted most of their misconceptions. This video depicted some metabolic reactions at the molecular level. Students’ misconceptions were first identified; based on them, an instructional intervention was designed to help students develop better, well-constructed conceptual schema (posttest). Evidence presented in the sample suggested the use of multimedia in helping students understand biochemistry was effective. An exploratory mixed methods design was used as a first stage to pilot any misconceptions among biochemistry students. A case study was conducted to investigate
if graduate chemistry major students had any misconceptions on metabolism ($n = 6$).

Based on the misconceptions found, the video was created to help undergraduate students develop a proper scientific understanding of the main concept targeted by this dissertation, which was chemical potential energy. The first phase of this research included quantitative validation of the instrument used ($n = 45$) and the second phase involved a phenomenological study where 11 graduate non-chemistry major students volunteered to participate. Many misconceptions were revealed by this study and most of them seemed to be prevalent and quite persistent.
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CHAPTER I

INTRODUCTION

The question of how to improve students’ understanding of chemistry concepts has been studied for the past decades (Chiu, 2007; Gabel, 1993; Saat et al., 2016; Visser, Maaswinkel, Coenders, & McKenney, 2018). Chemistry is perceived to be a difficult subject, and the vast majority of students take core chemistry courses only because they are required for their degrees. Their only motivation is usually to obtain a passing grade in it in order to continue in their fields. Specialized language, mathematical nature, and the amount of materials needed to be learned make chemistry difficult (Markow & Lonning, 1998). In addition, the abstract nature of chemistry concepts makes them hard to teach (Gabel, 1999). Students hold some misconceptions about difficult subjects, which might be due to factors such as the complexity of the subject itself or students’ own background knowledge (Johnstone, 2000).

Likewise, biochemistry is a difficult subject for both students and teachers according to Wood (1990). If students are to learn new biochemical concepts, then these misconceptions must be addressed and diminished. Researchers have concluded that instructors have to take students’ misconceptions into account if they want to help them acquire meaningful, scientific knowledge (Regis, Albertazzi, & Roletto, 1996). The presence of misconceptions in students’ minds interferes with the attainment of conceptual understanding in a topic and, thus, subsequent learning (Sreenivasulu & Subramaniam, 2013).
Many entry-level biochemistry students have trouble acquiring skills necessary to study metabolic pathways according to Anderson and Grayson (1994). Metabolism is usually taught by the traditional approach where memorizing the pathway and the chemical structures is necessary. Each metabolic pathway is usually taught as a module and usually knowledge transfer is not promoted between these modules. Anderson and Grayson (1994) proposed an alternative approach to teaching carbohydrate metabolism in order to induce long-term learning. This approach was designed to promote understanding rather than memorizing of metabolic pathways and to foster learning that would enable students to transfer their knowledge and apply skills to any metabolic problem they might face in the future.

This approach was similar to the "thinking curriculum" approach in which educators highlighted the importance of the studied materials for their students to enhance motivation and metacognition (Otero & Gray, 2008; Rickey & Stacy, 2000). Anderson and Grayson (1994) developed this instructional approach by interviewing nine post-graduate students in order to obtain their perceptions of the instructional approach, method of assessment, and goals of the undergraduate biochemistry course. Based on this questionnaire, they determined a set of goals for teaching a course, how it should be taught, and how students should be assessed. This approach focused on helping students understand why, where, how, and to what extent the metabolic pathways functioned in an integrated manner. The students were given handouts to minimize memorization. To promote transfer of knowledge, pathways in each module were related to those covered in other modules. Problems were presented to students in an interactive teaching approach.
using tutorial classes. The study reported an increase in students’ posttest scores compared to their pretest scores using this alternative approach (Anderson & Grayson, 1994).

**Instruction and Misconceptions**

One of the most effective areas of chemistry education research is the study of identifying misconceptions (sometimes referred to as naïve conceptions). Having knowledge of commonly held misconceptions could provide educators with insights into designing curriculum, materials, and test questions. Becoming familiar with common misconceptions is the first step in creating an instructional environment that acknowledges and engages students’ pre-concepts (Kahveci & Orgill, 2015, p. 154). Misconceptions were found in all areas of sciences, which included chemistry (Taber, 2002, p. 5).

Chi (2005) investigated why some misconceptions in the sciences were hard to eliminate. The researcher divided the processes associated with misconceptions into two main categories: emergent and direct. Next, in order to discriminate between these two types of misconceptions, Chi chose two fundamental processes normally taught to eighth grade students (i.e., circulation and diffusion) and found that *emergent processes* such as diffusion of a dye in water were associated with persistent misconceptions. *Direct processes* such as the flow of blood in human circulation were associated with misconceptions that were “not robust” (Chi, 2005). Since some misconceptions are hard to eliminate, educators can improve students’ learning by making instruction more meaningful, which should help them avoid these misconceptions.
Diagnosing Misconceptions

Educators have used several tools to diagnose misconceptions including concept mapping, concept inventories, three-tier tests. Two reasons researchers have developed such tools are the need for (a) intact, coherent knowledge and (b) the difficulty of eliminating misconceptions once created. To develop these assessments, qualitative techniques (e.g., think-a-loud interviews that used open-ended questions), quantitative research methods such as surveys, or both could be used in a mixed-method approach (Hamouda, Edwards, Elmongui, Ernst, & Shaffer, 2017; Margulieux, Ketenci, & Decker, 2019; Sreenivasulu & Subramaniam, 2013). Application of these instruments includes the need to test students’ background knowledge, which is usually done by using multiple-choice questions (e.g., concept inventories) or three-tier tests, which query students’ knowledge, reasons they selected their answers, and their self-confidence about the answer they gave in the first-tier (Karpudewan, Zain, & Chansegaran, 2017, p. 35).

Rationale, Purpose, and Research Questions

Rationale and Purpose

The current study investigated misconceptions students had about metabolism by focusing on the origins of these misconceptions and proposing a way to confront or minimize these misconceptions while allowing for better learning gains. The ultimate goals were to help students improve their conceptual understanding of the general chemistry concepts that impacted metabolic pathways and to develop sustainable understanding for this topic.

For this study, the instructional methods consisted of a multimedia video that targeted students’ misconceptions about metabolism. Identifying and characterizing
these misconceptions could improve the cognitive processes by highlighting them to help instructors avoid them. If instructors knew about the misconceptions in a particular area, they could better prepare their course materials and tests. The fundamental need for such a research project rested on the lack of previous research studies conducted on misconceptions regarding metabolism in terms of chemical potential energy.

**Research Questions**

The following research questions guided this study:

Q1 What misconceptions do biochemistry students have regarding metabolism? What factors can contribute to these misconceptions?

Q2 Is there a relationship between students’ improvement on the posttest, and their prior background knowledge or gender?

Q3 To what extent does the use of a multimedia video designed to confront these misconceptions help students to reduce their misconceptions across both genders?

Q4 How do students perceive the usefulness of this video in terms of confronting and reducing these misconceptions?”

In the pilot study, interviews with six graduate chemistry major students revealed some misconceptions and some improper terms students used to describe how they came to their answers. The pilot study helped determine what areas undergraduate students had problems understanding when it came to glucose metabolism. 45 undergraduate students participated in this phase, and they seemed to struggle in understanding some general chemistry concepts that could have an impact on their learning transfer from general chemistry courses to biochemistry courses. The quantitative data showed an increase in students’ learning gain when the multimedia video was used.

In the dissertation study (n = 11), more misconceptions were diagnosed among graduate non-chemistry major students, and the focus was on the origins of these
misconceptions so educators could pay attention to these sources. In-depth interviews were used to diagnose students’ misconceptions regarding metabolism in this study. Participants were given open-ended questions where they described their answers and how they came up with them. These think-a-loud interviews revealed if students either developed the correct scientific understanding or if they held misconceptions. One of my interests was to identify the origins of some common misconceptions.

**Research Hypotheses**

I think misconceptions about metabolism might be due to students’ misunderstanding of some chemical and biochemical concepts (Q1). In the pilot study, I conducted in-depth interviews to develop insights about a number of misconceptions held by graduate chemistry major and undergraduate non-chemistry major students. Chemical potential energy was a specific concept targeted in the current study. Many textbooks do not explain major metabolic pathways in terms of their chemical potential energies. They showed pathways such as glycolysis and oxidative phosphorylation processes as flat, linear series of reactions; this implies no difference in the chemical potential energy between reactants and products. In my opinion, this type of visualization could lead to many misconceptions. In addition, teaching these pathways in a linear fashion encouraged rote learning. For example, instructors might tell students why glucose should be phosphorylated to produce glucose-6-phosphate before further oxidation occurred. Unfortunately, this did not change the fact that students would probably memorize this step. Ignoring this essential factor, chemical potential energy, could lead students in only one available direction—rote learning. These misconceptions were revealed when students were shown a diagram that was superficially different from the
one used in their lectures. For example, if they were used to seeing the reactions in glycolysis shown as a vertical list (see Figure 1), they often did not recognize it when shown in a horizontal list (see Figure 2). The participants from the pilot study reported they had never seen Figure 2 before (Q1) and many participants who participated in the dissertation study were not sure if the graph was shown in their textbooks. According to Storey (1992), students might think bioenergetics are mysterious because they do not understand critical concepts such as entropy, equilibrium, change in free energy (ΔG), and adenosine triphosphate (ATP). Understanding the interactions between metabolic pathways as well as the regulation of metabolism is required for understanding metabolism. I developed a multimedia video to accomplish this goal (Q3 & Q4). Understanding the regulation of glucose metabolism cannot occur without the use of the graph showing free energy (see Figure 2) because the reactions targeted in the regulation process are reactions that have a free energy change greater than zero (i.e., non-equilibrium). These irreversible reactions are important regulatory points in glycolysis (Voet, Voet, & Pratt, 2013). Students could easily tell which reactions were at equilibrium just by looking at Figure 1 while they could not do so by using Figure 2.
Figure 1. Glycolysis (Voet et al., 2013).
Concluding Paragraph

The ultimate goal for the current study was to help students improve their understanding of the general chemistry concepts that impacted metabolic pathways. This study investigated misconceptions students had about metabolism and the origins of these misconceptions through two distinct studies: a pilot study that used an exploratory mixed-methods approach, and a dissertation study that was qualitative.

Figure 2. Diagram of free energy change in glycolysis (Voet et al., 2013).
Definitions

**Activation energy.** Enthalpy required to activate molecules for a reaction to proceed. It is required to initiate a chemical reaction (Allaby, 2019).

**Case-study.** A qualitative research design that uses in-depth, descriptive questions to provide insight into a unique issue with a case or more within a bounded system (Creswell, Hanson, Clark Plano, & Morales, 2007).

**Energy profile diagram.** Also known as reaction coordinate diagram—a diagram that represents the course of a chemical reaction with the potential energy as the “y” axis while the “x” axis is the reaction coordinate or the reaction progress (activated-complex theory).

**Enzymes.** Biological catalysts that lower, to a large extent, the energy of activation for a particular reaction (Allaby, 2019).

**Exothermic and endothermic reactions.** Chemical reactions that produce enthalpy are referred to as exothermic reactions. However, if a chemical reaction requires enthalpy to proceed, it is called endothermic (Lerner & Lerner, 2005).

**Experimental design.** Experimental research that uses randomization to claim certain outcomes are due to the effect of a given intervention (Usher, 2008).

**Gibbs free-energy.** Gibbs free energy is denoted ΔG and mathematically equals the change in the enthalpy minus the product of the temperature and the change in the entropy. The free energy can be used to predict the spontaneity of a process. If the free energy change is negative, the process is spontaneous (Lerner & Lerner, 2008).
Learning style preference. A description of someone’s preferred learning method.

Metabolism. A term used to describe a highly integrated network of chemical reactions within a living organism by which a living cell grows. These reactions are composed of two pathways: anabolism and catabolism (Kaczkowski, 2018).

Misconceptions. When students’ ideas do not match today’s scientific standards due to misinterpreting their observations and concepts through the lens of their pre-conceptions (Karpudewan et al., 2017, p. 91).

Multimedia. A combination of media and content including text, audio, and moving images either static or animated (Doyle, 2016).

The control points for glycolysis. The glycolytic reactions (1, 3 and 10) that are catalyzed by hexokinase, phosphofructokinase, and pyruvate kinase are the control points for glycolysis. These three reactions function far from equilibrium, and thus they are controlled by changing their enzymes activity and not by substrate concentrations (Voet et al., 2013).
CHAPTER II

REVIEW OF LITERATURE

In this chapter, literature relevant to the pedagogic problem, instructional intervention, and the theoretical framework is presented. The problem is many students in biochemistry courses develop misconceptions regarding metabolism. How an intervention that uses a multimedia video could help diminish these misconceptions is described. Finally, the theoretical framework for this study is discussed.

Preconceptions Versus Misconceptions

Misconceptions are students’ mental representations of a concept that do not correspond to the currently held scientific theory (Karpudewan et al., 2017, p. 133). Ideas students develop without having prior knowledge are described as pre-concepts. They differ from what are called school-made misconceptions and they tend to be unavoidable. Pre-concepts are ideas students bring from outside of classrooms. However, they were never taught; thus, neither the instructors nor textbooks are responsible for their development. Some of these pre-concepts are very persistent and are often resistant to change. An example of pre-concepts is some students think the wood of a tree comes from the soil. Students still answer this question this way even though photosynthesis is taught with the use of energy from sunlight, water, and carbon dioxide from atmosphere for the synthesis of carbon (the wood in the tree). These wrong ideas are usually evolved through observations but are missing the experimental proof for backing up these theories like ancient scientists. Most students do not link the knowledge
of everyday life to their courses. This failure of knowledge transfer presumably was due to the fact that these pieces of information were stored in two different compartments of their brains. This means this pre-concept resists the changes occurring when students are confronted with scientific, proper concepts in classrooms (Barke, Hazari, & Yitbarek, 2009, pp. 21-23).

**Diagnosing Misconceptions**

**Concept Mapping**

Organizing knowledge in a graphical format is called concept mapping and was developed by Novak (Moon, Hoffman, Novak, & Canas, 2011; Novak, 1990). *Concept maps* are graphical models consisting of two components—nodes that represent concepts and connections that represent prepositions to relate the nodes. These maps can reveal major misconceptions and which key concepts are either missing or present, and how well the learner integrated ideas and linked ideas to concepts. Depending on students’ cognitive learning styles, the concept mapping process might be interesting aspect for further study (Taber, 2002, pp. 33-47).

Concept mapping could be done by a student or a group of students in order to visualize a particular concept or a relationship between several concepts in a connected manner using connecting lines and arrows when appropriate to better represent this relationship. This process results in a two-dimensional diagram that displays the relationship among concepts. These student-constructed networks could be simple or convoluted, and they are usually read vertically downward (Anderman & Anderman, 2009). When students externalize concepts from their cognitive structure, the results could reveal several features: the concepts existing in their minds, the link between
concepts, and the conceptual change that takes place after a specific concept has been taught (Regis et al., 1996).

**Concept Inventories**

Concept inventories are standardized assessments used by instructors to measure students’ conceptual understanding and compare students’ learning outcomes across institutions, instructors, etc. (Goldman et al., 2010). In order to develop concept inventories, educators need to know what related misconceptions their students have. This usually is done in several stages. First, in-depth interviews are conducted to provide information about students’ conceptions and misconceptions (Hamouda et al., 2017). Next, based on those interviews, educators can detect and reveal those misconceptions, which are then inserted into a series of multiple-choice questions. Typically, each question has four possible answers; one represents the correct answer while the others are incorrect responses that often represent a misconception revealed from the previous stage. These inventories are strong tools to reveal how many students hold particular misconceptions.

In developing these concept inventories, the key feature that revealed these misconceptions was the information obtained from the interviewing stage (i.e., a qualitative mode), rather than the resulting assessment, which was developed using a quantitative mode (Margulieux et al., 2019). Also, these inventories did not expose the misconceptions unless they were followed up by one-on-one interviews. The goal of these interviews was two-fold: have each student try to explain what concept he or she missed and then have them attempt to develop a valid scientific conceptual understanding. When used as diagnostic tests, concept inventories seemed to be effective
in highlighting commonly held misconceptions so instructors could help students diminish their use. Misconceptions have been diagnosed using concept inventories (Briggs et al., 2017). Concept inventories can be used either before or after students have been taught target concepts. Several concept inventories have targeted general chemistry concepts such as thermodynamic and Gibbs free energy (Wren, 2014); however, none of these inventories studied the impact of these concepts within the context of biological systems, which was the topic of this dissertation.

Three-Tier Tests

Several studies examined students’ misconceptions in chemistry using three-tier tests (Kirbulut & Geban, 2014; Sen & Yılmaz, 2017). For example, a study was done to develop a three-tier test to reveal any misconceptions undergraduate students had on the topic of carbohydrates (Milenkovic, Hrin, Segedinac, & Horvat, 2016). In their study, teaching assistants were asked to propose misconceptions students might have on carbohydrates in order to incorporate them directly into the instrument called a Carbohydrate Diagnostic Test of Knowledge (CDTK). This test contained 14 tasks, each of which consisted of three tiers. To create distractors, Milenkovic et al. (2016) engaged organic chemistry teacher assistants (TAs) because they were familiar with students’ knowledge and their knowledge gaps. The first tier of this test was a multiple-choice content question that consisted of four options; only one of them was correct while the remaining three were distractors. The second tier also offered four answers; only one was correct while the remaining three distractors represented logical explanations of the distractors given in the first tier. Finally, the third tier of the question represented the confidence tier, which served as a determinant of students’ confidence in their answers.
provided for the first and second tiers. This study distinguished whether certain incorrect responses were attributed to the lack of knowledge rather than to misconceptions and, likewise, if some correct responses were attributed to the lucky guess rather than to genuine understanding.

**Misconceptions in Chemistry**

One of the misconceptions in chemistry is that students confuse molar mass, the mass of material given, and the reacting mass according to Kahveci and Orgill (2015). This might be due to their misunderstanding the concept of “limiting reagents” (Kahveci & Orgill, 2015, p. 155). Also, students struggled to understand the role of coefficients in chemical reaction equations. Students might have incorrectly included these coefficients when calculating molar masses. These misconceptions were confronted when students engaged in activities that required them to explicitly discuss the materials provided (Kahveci & Orgill, 2015, p. 155). According to Taber (2002), students thought a hydrogen-bond was a covalent bond; this was due to their exposure to hydrogen bonding in biology when they studied nucleic acids and protein before studying this concept in chemistry. If this bond was labeled to them as a “bond” without being clear, students then tried to make meaning of the information given to them in terms of their existing knowledge. The excessive coverage of the two types of bonding (ionic and covalent bonding) might have contributed to the presence of this misconception (Taber, 2002, p. 6). Specifically, knowing that hydrogen is a non-metal suggested to them that hydrogen could fit under the category of covalent bond rather than ionic. Since the students in Taber’s study had not been introduced to hydrogen bonding in their chemistry classes, they used the information they had so far to rationalize their ideas.
Misconceptions of Metabolism

The topic of metabolism is important in the field of biochemistry and most biochemistry curricula contain at least one introductory course on metabolism (Anderson & Grayson, 1994). The question of how to improve students’ understanding of carbohydrate metabolism has been studied by a number of researchers (Luz, Oliveira, & Poian, 2013; Milenkovic et al., 2016). Many students had a hard time understanding metabolism, which might be a consequence of traditional teaching methods that emphasized rote learning rather than understanding (Anderson & Grayson, 1994).

A widespread misconception regarding metabolism was found among high school students (Luz, Oliveira, & Poian, 2008; Luz et al., 2013; Oliveira, Sousa, Da Poian, & Luz, 2003). Students thought glucose was the sole metabolic fuel, disregarding other macromolecules such as lipids and amino acids that could be oxidized for ATP production (Oliveira, et al., 2003). In one study, a questionnaire regarding ATP production was used to detect misconceptions among people who were consuming a low carbohydrate diet or fasting (Luz, et al., 2008). It was scored as a misconception if students said ATP production fell during a low-carbohydrate diet and/or fasting, implying glucose was the only fuel available for ATP production. After eight months of designed instruction including lectures, discussion, and the use of models, this misconception was confronted. Luz et al. (2013) found students had this misconception because they failed to transfer knowledge from the biochemistry course they had had to their personal lives. Another study by Silva, Poian, and Luz (2005) conducted an intensive investigation to find why students held this misconception. They found seventh grade students did not hold this misconception; however, eighth grade students did. This finding suggested the
formal learning eighth grade students received was the cause of this misconception. Another source of this misconception was the way textbooks showed how carbohydrates were associated with energy production. They characterized proteins and lipids as only being structural and storage molecules. Additionally, only glucose metabolism was taught in high school, which reinforced this misconception (Silva et al., 2005).

Another study that investigated misconceptions about biochemistry was done on the topic of photosynthesis and plant respiration (Ünal, Coğtu, & Ayas, 2010). They stated that students had misconceptions about where the process of photosynthesis took place and whether oxygen was produced over an entire 24-hour day. They also found another misconception, which was water is the most important source of food for plants. These misconceptions were confronted by graphic explanations, chemical clarifications, and connecting integrations of the concepts related to the photosynthesis process. A two-tier test was used with a series of three stages to diagnose these misconceptions: defining the content, obtaining information about students, and developing a diagnostic test (Ünal et al., 2010).

Storey (1989) investigated misconceptions and textbook errors on the topic of metabolism and photosynthesis. He reported one important source of misconceptions: the use of wrong terminology by textbooks as well as by teachers. When instructors or textbooks used simplistic terminologies, students could develop serious misconceptions. For example, many biochemistry textbooks still used the term dark reactions to describe the second phase of the Calvin cycle of photosynthesis, implying photosynthesis occurred in the dark (Storey, 1989). The use of wrong terminology was mentioned by Barke et al. (2009). They wrote that as traditionally taught physical and chemical changes were
distinguished from one another. However, students might say dissolving sodium hydroxide in water would generate heat and thus it would be called exothermic reaction instead of saying exothermic process. This would cause a school-made misconception if instructors continued using these terms interchangeably (reactions versus processes; Barke et al., 2009, pp. 25-26).

Another factor discussed by Storey (1991) was many textbooks did not show the enzymes that catalyzed metabolic reactions above the reaction arrows and some products in these pathways were ignored. Furthermore, these textbooks did not tell students these metabolic pathways were diagrams or models drawn to help them understand biological concepts, which were developed from research. Instructors assumed students should know there are a huge number of “copies” of the intermediates (pools) and enzymes in cells; however, they assumed there was a neat, well-organized Krebs cycle. Instructors should remind students to think in the right way. To differentiate between a textbook view of the model (metabolic pathway) and the scenario that happens in reality, Storey (1991) suggested asking students: Why are the glycolysis reactions shown as being vertical rather than horizontal? Why does the Krebs’ cycle operate in a clockwise fashion? Storey (1992) wrote that bioenergetics remain mysterious because of the inadequate explanation about critical thermodynamic terms such as entropy, equilibrium, free energy (symbolized by G), and ATP. This dissertation explored these relationships.

**Origins of Misconceptions**

The origins of misconceptions in chemistry and biochemistry were described in several studies (Barke et al., 2009; Johnstone, 2000; Lee, 2004; Luz et al., 2013; Silva et al., 2005). One misconception in chemistry could occur when the learner is confronted
with ideas that originated from different levels of thought (see Figure 3). These levels are shown in the chemical triangle, which was introduced by Johnstone (2000) to explain the complexity of learning chemistry. It states there are three levels of thought: the macro and tangible, the sub-micro atomic (molecular), and the symbolic use of equations and representations. Unfortunately, when the learner is introduced to ideas from these levels simultaneously, then this could lead to many misconceptions. Conversely, the expert could use these levels to deeply understand chemistry topics while the novice could not. For example, a misconception might result when the teacher says hydrochloric acid dissociates in water to give a proton instead of saying it dissociates in water to give a hydronium ion. Another one could be saying “Oxygen takes two electrons” instead of saying one oxygen atom is taking two electrons (Barke et al., 2009, p. 27).

![Chemical Triangle](image)

*Figure 3. Chemical triangle (Johnstone, 2000).*

Having misconceptions might also be due to the complexity of the subject itself. Based on the chemical triangle (see Figure 3), professors often use examples from the macro world to explain something happening in the micro-scaled atomic world. Herein lies a source of misconceptions, which is the strength of the subject as well as the weakness of it. Chemists understand chemistry because they can interconnect among the
three levels of ideas. For a professor, transferring from one setting to another could strengthen his or her argument and provide alternative explanations; however, for the learner, it is hard to transfer from one level of thought to another. Much of the complexity of chemistry lies in the multiple transitions between the tangible and sub-micro levels. That not only confuses students but they also have a hard time connecting information from multiple levels. Unfortunately, students often see them as completely separate “worlds”; any attempt to connect them could lead to many misconceptions, especially when all three levels are presented at the same time (Johnstone, 2000).

Students tend to memorize abstract chemistry concepts rather than merely understanding them. Likewise, students have a difficult time in conceptualizing biochemistry topics (Lee, 2004).

Misconceptions are held due to the complex nature of chemistry concepts and because of the way the concepts are approached. Gabel (1999) indicated the complexity of chemistry has implications for the way chemistry is being taught. The abstract nature of these concepts makes them hard to teach without the use of analogies or models. The high density of chemistry concepts in elementary textbooks is partly responsible for this difficulty. The second origin of misconceptions is discussed in the theoretical framework of this study and is based on the following information-processing model. Barke et al. (2009) suggested that the complexity and the difficulty level of chemistry topics might have contributed to school-made misconceptions. Students developed a misconception about salt decomposition—when dissolving a salt, atoms of that salt will form ions through “electron exchange.” Students thought that when dissolving sodium chloride, the chlorine atom would attract an electron from the sodium atom and that would make two
ions: chloride, a negatively charged anion, and the sodium cation, which was positive. This was a wrong explanation for the hydration process of a salt where water molecules first break the salt lattice and then surround the newly formed ions. One source of this misconception was the use of the term *salt molecules* when the dissociation theory of Arrhenius was first postulated in 1884. Although, this term was corrected by the modern science, and its difficulty might have contributed to the development of the previously discussed misconception (Barke et al., 2009, p. 24).

**Theoretical Framework**

Several theories guided the development of this dissertation study, where both qualitative and quantitative methods were used in the pilot study, while the phenomenological approach was used in the main study. Constructivism and information-processing theories both provided interpretations for why people would develop misconceptions rather than an appropriate understanding of concepts. Furthermore, dual-coding theory was used to support the use of static or animated graphics.

**Constructivism**

Bommarito and Matsuda (2015) wrote that constructivism is the view that knowledge is created and shaped by the complex interaction of variables such as language, culture, and social practices in a given context. Based on this view, knowledge does not exist out there in the world for someone to objectively discover, but rather it comes into existence through the engagement with people and the external world. That is, knowledge is constructed via these interactions—where individuals integrate new knowledge with existing knowledge. Constructivism places the learner at the center of
analysis, highlighting the process by which prior knowledge interacts with environmental factors such as verbal cues and others’ ideas.

One principle of constructivism is that people process information from the external world through the lens of their own experiences according to Bommarito and Matsuda (2015). Another principle emphasizes how those experiences are constrained by the world itself; as individuals engage with the world, their prior knowledge is refracted through encounters with new, external phenomena and reassembled in novel ways. The result of this process of assembly is the development of new knowledge. Constructivism and learning are connected through the importance of prior knowledge. Constructivism scales our perspective to the level of the individual, the learner, and focuses on the unique characteristics each learner possesses such as the knowledge they already possess, personal motivations, goals, and objectives for learning. From a constructivism perspective both learning, in particular, and education, in general, are seen as highly individualized processes from a constructivism perspective (Bommarito & Matsuda, 2015). Pienta, Cooper, and Greenbowe (2005) stated each learner has a unique need and prior knowledge on which to build new learning according to constructivism. This implies knowledge cannot be transferred fully intact from the instructor to students (Bodner, 1986; Pienta et al., 2005, p. 14). Rather, every student handles the information given by the same instructor in a different manner. Consequently, this causes a lot of misconceptions that inhibit the learning process.

In addition to prior knowledge, students’ mental models have a great effect on their learning (Johnstone, 2000; Seel, 2001; Suits, 2015). According to constructivism, people create internal abstract models of external situations called mental models
Mental models are personal, internal representations of the external, real world. Mental models are constructed when needed to master a learning situation with its particular demands (Seel, 2001). Each individual develops different mental models based on their unique experiences, perceptions, and ideas (Suits & Srisawasdi, 2013). Mental models are used to reason and make decisions; however, they can lead to possible misconceptions.

**Information-Processing Model**

Based on the information-processing model, students’ background knowledge can affect new information being learned (Johnstone, 2000). Thus, eliminating misconceptions from their knowledge could lead to better learning fulfillment. Based on this model, misconceptions could originate beginning with perception, which is how we detect information from our senses. Perception is what is used by our minds as a filter to focus on some stimuli while ignoring other stimuli. This filtered information is then admitted into the conscious part of our minds where it is processed by working memory. Here the information is compared with previous knowledge to be modified and stored or rejected. If it is stored, it should be incorporated into a schema (i.e., organized knowledge) in long-term memory. If there is no link between the new information and a student’s prior knowledge, then it is stored as fragments (i.e., unattached information); hence, the new information is easily lost. As a consequence of bending new knowledge, a misconception could occur (Johnstone, 2000). Figure 4 shows the information-processing model.
Another way that students’ background knowledge can affect the new knowledge (Johnstone, 2000) in an adverse way is based on their previous coursework. For example, a lack of sufficient background in organic chemistry could affect students’ biochemistry learning. Thus, misconceptions can be transferred from students’ previous courses, which can adversely affect their learning.

**Dual-Coding Theory**

Dual coding theory (DCT) is a general theory of cognition that explains issues such as various forms of literacy, intelligence, expertise, creativity, and the evolution of human minds (Sadoski, 2015). Dual coding theory was first introduced by Paivio (1979) and it is relevant to educational technology, particularly multimedia learning. Dual coding theory assumes all cognition involves the activity of two qualitatively different mental codes—a verbal code and a nonverbal code. The verbal code features the production and reception of language while the nonverbal imagery code (i.e., visualization) processes nonlinguistic knowledge of the world in the form of mental images. Depending on the task performed, these two codes can work in three different ways:

- **Storage**
  - Sometimes branched
  - Sometimes as separate fragments

- **Working Space**
  - Interpreting
  - Rearranging
  - Comparing
  - Storage Preparation

- **Feedback Loop for Perception Filter**

*Figure 4. Information processing model (Johnstone, 2000).*
modes: independently, in parallel, or via interconnections. Flexibility found in human cognition is due to differences between these codes (Sadoski, 2015). Coding refers to the ways the external world is captured in mental representations—the internal forms of information stored in memories (Sadoski & Paivio, 2001). Sadoski (2015) wrote that one key principle of DCT is that memory can be enhanced when information is stored in both codes (i.e., dual coding) because the effect of the codes is additive. Dual coding theory assumes code additivity—information can be learned better if the same information is presented both in verbal and nonverbal modes. This does not mean the information is encoded in just one or the other of these two codes. When instruction features these codes interconnected together, research found it to be more effective than verbal presentations alone or pictorial presentations alone (Sadoski, 2015).

Mental imagery is hypothesized to be part of the verbal thought process including visual or auditory images of words (Paivio, 1979). Paivio (1979) highlighted the benefits of using these images on students’ retention rate, reporting the rate of the recall was better when imagery instructions were used: “The imagery mnemonic systems were based on the implicit assumptions, among others, that concrete objects and events or their verbal surrogates, are easier to remember than more abstract stimuli” (p. 177). An extra transformation is involved when coding verbal representations as verbal representations must be triggered after non-verbal representations have been activated. As a result, the availability of verbal codes is lower compared to non-verbal codes (Paivio, 1979, p.179).

Working memory (WM) is closely related to DCT because it can handle only a very limited number of novel interacting elements—probably two or three elements (Paas, Renkl, & Sweller, 2003). Mayer (2014) wrote that cognitive load theory is
concerned primarily with the acquisition of biologically secondary knowledge, which is cultural knowledge people have not evolved to acquire. One of the five principles in cognitive load theory is “the information store principle” (Mayer, 2014, p. 29). Working memory occurs during any conscious cognitive processing of information and is inadequate to account for most intellectual activities. Long-term memory (LTM) greatly expands the amount of cognitive information that can be processed. LTM stores information as schemas, which are cognitive constructs that can store multiple elements of information into a single element with a specific function. All the information stored in LTM has been learned and is responsible for most cognitive activities in which the individual engages.

A schema can be characterized as being “a mental framework…that arises out of past experience, growing and differentiating throughout childhood, and places new experiences in their appropriate context and relation” (Kent, 2006, p. 1). Schemas are considered to be the building blocks of mental modeling (Seel, 2001). Different individuals possess distinctly different schemas. Consequently, students can receive the same information presented by an instructor but they process it differently.

Working memory capacity is important when the complexity of the task is considered. A problem of how to introduce complex materials at one time was investigated by Hessler and Henderson (2013). The learner could digest a particular amount of information given in one setting; however, if the complexity of this information was considered, the amount would decrease because it was coupled with other processes such as reasoning or analyzing. Giving too much information at one time could cause cognitive overload. The study by Hessler and Henderson investigated the
possibility of designing a computer-based case study to teach complex materials to
nursing students while reducing the cognitive load. They investigated how to increase
the amounts of objects learned by nursing students by chopping the information into parts
using a clickable, computer-based case study. In this method, the students learned the
first object before going to the next one; this should guarantee better information storage
in long-term memory.

Gyselinck, Cornoldi, Dubois, De Beni, and Ehrlich (2002) used the dual-task
paradigm to present texts dealing with basic science concepts such as static electricity
and gas properties to learners. Some of the texts included illustrations, while the others
did not. Prior to the intervention, participants were tested for spatial working memory
capacity and randomly assigned to either the text only or text plus illustration condition.
While reading the text or text plus illustration, participants engaged in one of three
concurrent tasks: tapping a spatial pattern, repeating a series of syllables, or a control
task. Results indicated participants engaged in the concurrent spatial pattern task had
impaired comprehension in the text plus illustration condition but not in the text-only
condition. Further analysis indicated participants who scored high in spatial working
memory benefited most from the text plus illustrations condition but their performance
was most inhibited by the concurrent spatial pattern task. These results indicated spatial
working memory capacity played a role in processing images during learning tasks
(Gyselinck et al., 2002).

**Phenomenology**

Phenomenology is a philosophy of knowledge and a qualitative research approach
that is popular in education and in both social and health sciences. It studies the meaning
of a phenomenon or a concept as shared by several individuals of their “lived experiences” (Anderman & Anderman, 2009). Phenomenologists focus on describing and interpreting what participants have in common as they experience a phenomenon. It is used to describe and interpret what participants have in common as they experience a phenomenon. To describe this experience, data should be collected from all of the individuals, which is often done with heterogeneous groups of 3-15 participants (Creswell, 2013, pp. 76-79). Phenomenology is not only a descriptive study, it provides interpretations to lived experiences, without attempting to explain them (Creswell et al., 2007).

**Use of Multimedia Instruction**

Rieber (1990) offered students a computer-based lesson on Newton’s law of motion using either static or animated graphics. He found students in the animated graphics group had a better understanding of the concepts of Newton’s law than did those in the static graphics group (Rieber, 1990). The potential benefits of using animation, visual cueing, and a combination in a multimedia environment were investigated by Lin and Atkinson (2011). Undergraduate students’ acquisition and retention of scientific concepts were studied using graphics (animated versus static graphics) and visual cueing (visual cues versus no cues) as factors. The rate of retention of the scientific concepts was higher in the animation group. Furthermore, students who were given visual cues displayed more instructional efficiency and consumed less time than the other group (Lin & Atkinson, 2011).

Yang, Andre, Greenbowe, and Tibell (2003) investigated the impact of computer animations illustrating chemical reactions that occurred inside a battery on students
enrolled in a college introductory chemistry course. Students were given lectures on electrochemistry and how batteries worked using either animations or static diagrams. Students also were given a chemical knowledge test and a Flashlight pre-test; these tests were used as covariates. The students then completed two chemistry content exams before they received the lectures. Students in this study were classified as low or high spatial ability based on a spatial ability test given after the lectures. Providing the content with an animation had a more positive effect on students’ performance than the static diagrams. The results showed instructor-guided animations might help students acquire a better understanding of targeted chemistry concepts (Yang et al., 2003). The use of animation in providing instruction has not been limited to school settings. The use of animations was found to improve diabetes literacy among limited educational fulfillment groups of Latinos and Hispanics (Calderón et al., 2014).

Mayer (2014) wrote that another principle in cognitive load theory, as mentioned previously, is the borrowing and recognizing principle. According to this principle, people can obtain knowledge from others by listening or reading. This secondary knowledge could be combined with already existing information, resulting in editing the information stored in long-term memory. The ability to acquire biologically secondary information by listening is a biologically primary task we have evolved to acquire. However, knowledge obtained by reading is a biologically secondary task one has not evolved to acquire from others. This implies it might be more beneficial if one looked at a figure with the association of a narration rather than a text. An important assumption in cognitive load theory is the main purpose of instruction is to assist individuals in obtaining knowledge from other people. Therefore, how to present information and what
activities individuals engage in are important issues according to cognitive load theory (Mayer, 2014, p. 31).

Educators designing materials for interventions have access to a variety of ways to represent information to learners including text, images, and animations. Kotevski and Tasevska (2017) wrote that implementing multimedia in education has proven to bring numerous benefits to enhance students’ learning by enhancing their cognitive abilities, ease in understanding abstract content, and raising retention rates. However, for an educational system, information provided by multimedia technologies might not be sufficient to achieve the desired development. To achieve these educational advancements, a multimedia system should be equipped properly, educators who present the multimedia content should be interested in presenting it, and the events provided should be organized. Analysis and an evaluation should be made to decide if implementing multimedia systems would support the purposes of their use as well as if educational development would occur (Kotevski & Tasevska, 2017). In general, the use of multimedia should be evaluated to weigh the benefits of using and not using the technology for educational purposes. For example, if an animation or simulation was provided to students without evaluation, it would cause unwanted effects. We should keep in mind the purpose of using such a multimedia system. Is it to test a student’s knowledge in a specific content? If so, experts in the field of the study should measure content appropriateness to evaluate if the multimedia system is testing the content that should be tested or different content. If the use of animation was to confront a specific misconception, the educator should make sure the animation helped improve students’ understanding and did not produce new misconceptions.
Teplá and Klímová (2015) developed an educational multimedia program to help facilitate high school students’ comprehension of the electron transport system. This multimedia program consisted of a series of interactive dynamic animations. Visualizations helped teachers explain the material covered more clearly and thus avoided an incorrect understanding of the abstract scientific concepts. This educational system was effective for teaching biochemistry for high school students and got a positive response from teachers who used it (Teplá & Klímová, 2015).

Schönborn and Anderson (2006) wrote that external representations, such as dynamic visuals and pictures, are essential for teaching and understanding biochemistry. These representations enable learners to develop and construct meaningful mental models of biochemical phenomena. It is more suitable to use animated computer images in teaching three-dimensional biomolecules and dynamic processes. However, external representations might be more powerful in teaching and learning dynamic metabolic pathway than a static process, for example. Dynamic representations would not always be more useful than static ones because of the cognitive overload associated with animated figures (Schönborn & Anderson, 2006).

**Concluding Paragraph**

To summarize this chapter, misconceptions are developed when students are in an educational setting and can be transferred from one course to another. Misconceptions are difficult to extinguish but multimedia instruction might provide an effective means of instructional intervention. Constructivism and information-processing theory provided the theoretical framework for understanding how misconceptions develop. Multimedia learning theory described plausible instructional interventions.
CHAPTER III

METHODOLOGY

This chapter summarizes the methods used in the pilot study and the dissertation. These methods were used and developed in my pilot study, which was an exploratory mixed-methods approach. It was used to assess students’ conceptual understanding of some general chemistry concepts that impacted the understanding of metabolism. Conversely, the dissertation focused on using a phenomenological approach in order to get an in-depth understanding of why students developed superficial rather than meaningful learning strategies. Also, the current study explored how an innovative instructional method (i.e., a multimedia video) could be designed to enhance the learning of students without introducing any new misconceptions.

Methodological Approach and Justification of the Methods

The Pilot Study

Pragmatism was the paradigm that provided a foundation for the mixed-methods approach used for the pilot study. The mixed-methods research design employed an approach where I used techniques that best solved the research problem and answered its research questions. It valued both objective and subjective knowledge. One principle in pragmatism was that answering the research question was more important than the methods and underlying theories; as a consequence, both qualitative and quantitative methods could be used in one study (Creswell & Plano Clark, 2011).
The qualitative design used for the pilot study was a case study. The focus in case studies is on an issue with the case selected to gain an in-depth understanding about the issue. This means the focus in case studies is not on the individuals but rather on the issue. Case study research is a qualitative approach in which the inquirer explores a bounded system through in-depth data collection including interviews (Creswell et al., 2007). The focus for the pilot study was on misconceptions students held on metabolism. The case study approach was the best fit for this study and provided an in-depth understanding of misconceptions students had.

Ideally, quantitative data provide a general understanding of a problem while qualitative data provide more in-depth understanding. In most cases, one data source might be insufficient. The results of quantitative and qualitative methods, however, draw different pictures about the research, which was why a combination of both methods in a mixed-methods approach provided the full picture I wanted to obtain. In some cases, a need existed to enhance the finding with a second method or to generalize some exploratory findings. A limitation of one method could be compensated as well by the strength of the other method. Thus, the use of mixed-methods research might offset the weakness of the use of either a quantitative or a qualitative research method alone (Creswell & Plano Clark, 2011).

Mixed-methods design is an integrative approach that began in the late 1980s after the paradigm war had ended (Creswell & Plano Clark, 2011). For the pilot study, a mixed-methods, sequential exploratory design was used. This design consisted of two distinct phases where I started by qualitatively exploring a research problem using a case study approach followed by a quantitative phase where I developed an instrument based
on the first phase to use in subsequent data collection (Creswell & Plano Clark, 2011).

Figure 5 shows a schematic overview of the design used for the pilot study.

![Sequential Exploratory Design](image)

**Figure 5.** Sequential exploratory design (Plano Clark & Creswell, 2008).

**The Dissertation**

Phenomenological studies describe what all participants have in common as they experience a shared phenomenon. Phenomenologists work much more from participants’ specific experiences rather than explaining those experiences using researchers’ statements. The inquirer collects data from individuals who have experienced a phenomenon and then develops a description of the essence of the experience for all the individuals (Creswell et al., 2007). Realistically, I decided to use only a qualitative method in the dissertation as phenomenology allows more rich information about the diversity of a target population. Also, this method helped alleviate any adverse feelings
students from sport and exercise science might develop if they felt they were “under the microscope” or they were the only students who might develop misconceptions about metabolism. Phenomenological studies focus on every individual who shared a common experience with other participants and it allowed me to extend this study to engage more students from chemistry and other related fields. This phenomenological study would not have been possible without applying the pilot study to first quantitively validate the used instrument. In addition, the feedback I received from the participants in the pilot study enriched the main dissertation.

**Learning Style Preferences**

In the field of education, many theories that attempted to describe how people think and learn were proposed to classify students into distinct groups. These distinct groupings included visual versus auditory, global versus analytic, or inductive versus deductive. According to Singh (2016), different learning styles including visual, auditory, reading/writing preference, and kinesthetic might be considered in implementing instructions. These learning styles are usually based on students’ preferences rather than learning approaches (Singh, 2016). Learning styles are not students’ abilities but rather their preferred ways of using these abilities. Students’ learning styles differ in their natural, habitual, and preferred ways of processing and retaining new knowledge and skills. Learning styles are not fixed modes of behavior but rather, they can be extended and modified; individuals might have some strong style preferences on different situations and tasks. Numerous learning style instruments, often written surveys, have been developed for research and pedagogical purposes. Although individuals differ in how they prefer to process and acquire new information, these
preferences have been a source of great controversy among educators. While opponents of learning styles assessments claimed that tailoring instruction to students’ individual preferences did not guarantee better learning outcomes, proponents believed learning styles could be measured and used as a valuable educational tool. Diagnosing students’ learning styles and matching them to teaching methods could enhance education (Hatami, 2013).

**Researcher Stance**

I taught biochemistry courses for two years and know how hard it is to cover the topic of metabolism. I experienced how students struggled understanding biochemistry concepts. They tended to memorize the different metabolic pathways. I found myself engaged in answering these questions, why biochemistry is a hard subject, and how to improve students’ understanding to these biochemistry concepts. I felt the excessive coverage of glycolysis and glucose metabolism in general made it the most important molecule in the body in students’ minds. Every biochemistry curriculum contained detailed information about glucose, and that made students believe that if we did not consume glucose in our diet, our health would be affected. Educators should be aware of the materials being taught as well as the language used in classrooms. When students ask a question about metabolism, the instructor tends to dig deeper to answer that question and that could confuse the student. An in-depth explanation given by the instructor requires some knowledge in chemistry regardless of the student’s major. That represents another challenge in teaching biochemistry since most of the students taking biochemistry might be non-chemistry majors because biochemistry courses are required
in many disciplines. Instructors tend to simplify the materials in order to reduce their difficulty; however, this simplification can generate misconceptions.

**Participants**

**The Pilot Study**

The target population of the pilot study was students 18 years of age and older enrolled in university level biochemistry courses. The setting was a mid-size, public, doctoral research university in the Rocky Mountain region that houses about 200 academic programs. The accessible population for the case study was graduate chemistry major students \((n = 6)\); for the quantitative part of the pilot study, it was undergraduate non-chemistry major students \((n = 45)\) enrolled in courses that covered the topic of metabolism such as Exercise Physiology I and II (SES322 and SES324). These courses were designed for undergraduate students who were non-chemistry majors; the main majors for students in these courses were coaching, athletic training, physical education, and exercise science.

**The Dissertation**

The accessible population for the dissertation was students who were taking the course Metabolism (SES626). The students who populated this course were non-chemistry majors; the participants who took this course were majoring in exercise science and biomechanics. Initially, I tried to recruit participants from the course General Biochemistry II (CHEM482/582), which was designed for graduate and undergraduates with different majors; however, none of the students who enrolled in this hybrid course participated in the dissertation.
Instrumentation

The Pilot Study

**Overview of metabolism.** An overview of the major metabolic pathways is shown in Appendix A. Some keywords were hidden in this overview and students were asked to fill the blanks in the diagram. All the participants regardless of their prior knowledge filled the blanks in this overview. The overview shows the interconnection between several metabolic pathways, and the students who had an idea about the pathways, such as glycolysis, could fill in the blanks. The main reason for using this overview was to exclude any student who did not have sufficient knowledge to participate in this study. In addition, this overview was used in interviews to test whether or not students could see the interactions between various metabolic pathways. This overview was used only in the pilot study since all the participants regardless of their majors had no problems with the terms covered by the overview. This overview was used only to test if both chemistry and non-chemistry major students would fit in this study.

**Demographic questionnaire.** After signing the consent form (see Appendix B), students were given a demographic questionnaire (see Appendix C). Demographic variables included age, race, and gender. In addition to these variables, students were asked to report their attitude about chemistry and to list the courses they had taken regarding metabolism. Also, by knowing these characteristics of the participants, I was able to draw a conclusion and interpret the results of the study.
**Open-response test for the pilot study.** Students were provided with a short open-ended test (as pre and posttests) with eight items (see Appendix D) as a part of an experimental design. The possible scores of this test ranged from zero to 20 since the items had sub-sections. The language in this test was understood to chemistry and biology major students and the test took no longer than 15 minutes. Questions for this test were created by an expert—a professor in the chemistry department. The scores of the pre-test were used to assess students’ prior knowledge and to categorize the students into two groups of high and low prior knowledge.

**The Dissertation**

The overview of metabolism (see Appendix A) used in the pilot study was excluded for the dissertation for several reasons. This overview did not really discriminate among participants based on their prior knowledge. In addition, it was hard to grade this overview or come up with a rubric that could be used to assign scores for the participants on this overview. Thus, this overview was eliminated for the dissertation.

**Demographic questionnaire.** The same demographic questionnaire used in the pilot study was used in the dissertation (see Appendix C). The purpose of this questionnaire was to help in describing the sample in addition to knowing if the participants (mainly non-chemistry majors) had previously taken any chemistry courses.

**The Object-Spatial Imagery and Verbal Questionnaire.** Only the participants in the dissertation took the Object-Spatial Imagery and Verbal Questionnaire (OSIVQ) (see Appendix E). The OSIVQ was developed by Kozhevnikov and colleagues and it consists of 45 questions that categorize students according to their learning style preferences (Blajenkova, Kozhevnikov, & Motes, 2006; Blazhenkova, & Kozhevnikov,
Learning style preferences represent how individuals prefer information to be presented for them (i.e., textual or graphical). The OSIVQ has been validated and tested for reliability in categorizing participants based on their preferences into either verbalizer, spatial, or object visualizers (Blajenkova et al., 2006; Blazhenkova & Kozhevnikov, 2009; Kozhevnikov et al., 2005). In addition to the verbal scale, the OSIVQ consists of two scales: an object imagery scale that assesses students’ preferences for visual representations and colored pictorials and a spatial imagery scale that assesses their preferences or processing schematic images and spatial transformations. This test will also distinguish visualizers from verbalizers (Blazhenkova, & Kozhevnikov, 2009; Hilsenbeck-Fajardo, 2009; Kozhevnikov et al., 2005). Furthermore, this self-preferential learning style questionnaire was used in a midsize-public university in biochemistry courses to categorize students based on their learning style preferences where the setting was similar to the one in this current study (Hilsenbeck-Fajardo, 2009).

Open-response test for the dissertation. The questions from the open-response test for the pilot study (Appendix D) were edited with the adaptation of some questions from a biochemistry textbook written by Voet et al. (2013). Questions on this test targeted various concepts in chemistry such as oxidation-reduction reactions and Gibbs free energy. The students were asked to answer each question and provide an explanation for their answers. This test consisted of five questions based on the misconceptions found in the pilot study. A professor from the chemistry department checked if these questions constituted a valid method to assess for the presence of these misconceptions. This open-response test is shown on Appendix F.
**Final interview.** In addition to the interview conducted after the posttest, after getting the intervention, the participants were interviewed to provide me with feedback about the treatment they received. This interview helped in getting more in-depth understanding regarding the students’ perception about the treatment they received. Appendix G provides the semi-structured questions used in this interview.

**Procedures**

The dissertation was based on a pilot study that was implemented one year before the dissertation took place. Insights gained from the pilot study were used to inform the design and methods for the dissertation.

**The Pilot Study**

The pilot study was used to address a gap in the literature discussing the concepts students struggled to understand on the topic of metabolism, I started an exploratory sequential design where qualitative data were collected and analyzed first before collecting quantitative data. The first stage included a case study that revealed what concepts students had difficulty understanding and investigated what misconceptions they had. An intervention was developed based on the misconceptions found to collect quantitative data to investigate how widespread these misconceptions were among undergraduate students. This intervention was a multimedia video created to help students get a better understanding of a particular concept—chemical potential energy.

**A case-study.** The study was first applied to graduate students from the chemistry department to test the difficulty of the questions. An e-mail was sent to all of the graduate students from the chemistry and biology departments to seek volunteers. Five white female and one white male graduate student participated in this case-study.
They were chemistry majors from the master’s and doctoral levels and not all of them were teaching assistants. This stage determined the concepts that should be included in this study, diagnosed some misconceptions graduate students had, and reported the level of the difficulty of the questions used. On a scale of 3 where 1 represented the easy level and 3 was the hardest, the graduate students ranked the questions to be 2 out of 3 difficulty level. First, the students were given an overview of metabolism (Appendix D). Students were then given a pretest, which was the open-response test for the pilot study (see Appendix D); once the participant finished taking it, a think-aloud interview was conducted to detect any conceptual misunderstanding the graduate student had. The interview consisted of questioning students to explain their responses on this pretest and how they came up with their answers. All participants were interviewed immediately after taking the pretest. The interview was audio-recorded to be transcribed later. The interviews took no longer than 10 minutes since the participants had already answered the questions in the pretest. The results from the pilot study are reported in Chapter IV.

A concurrent approach. Concurrent triangulation design was then used in the second phase of the pilot study to test the effectiveness of the video used. The results of both the qualitative and quantitative methods were integrated during the last phase—the interpretation phase. According to Plano Clark and Creswell (2008), this interpretation might strengthen the researcher’s claim by confirming the findings or explaining the lack of convergence, if any, between the qualitative and quantitative findings (p. 183).

The pilot study was conducted outside of the students’ classrooms so it would not take time away from instruction; thus, not every student in the class participated. The course was a lecture-type where face-to-face instruction was used. It had a capacity of 50
students per section. All the participants were white undergraduate students. The majority of participants were females (36 females and 9 males); most of them reported having a positive attitude about chemistry. There were no missing data in the pilot study; no students were excluded since all participants were able to complete the metabolism overview. A sign-up form was distributed in the selected classes for students to write their names and e-mail addresses if they were willing to participate and be contacted later.

First, the students were given an overview of metabolism to investigate their ability to take the pretest (Appendix A). Failing to fill in the blanks in this overview implied students had no clue about metabolism. Having the students first finish this open-response overview eliminated possible random choices and ensured the answers students gave were based on what they knew. Completing the overview took no more than five minutes.

Students were then given a pretest, which was the open-response test for the pilot study (see Appendix D); once the participant finished taking it, a think-aloud interview was conducted to detect any conceptual misunderstanding the student had. The interview consisted of questioning students to explain their responses on this pretest and how they came up with their answers. Asking participants how they came up with their answers revealed any misconception behind the wrong response. All participants were interviewed immediately after taking the pretest.

The last phase of the pilot study was developing a video that focused on addressing most of the students’ misconceptions. Students from different sections of the same course were randomly assigned to either the experimental group or the control
group. These sections were taught by different instructors. Data were collected over a period of three academic years (one year for the qualitative data; i.e., question preparation and conducting interviews; one year for creating the video; and one year to use the video and conduct the quantitative research).

**Experimental group.** Two weeks after taking the pretest, the video was shown to the experimental group right before taking the posttest, which was the same as the pretest (see Appendix D). The students in the experimental group were shown a video containing graphs relating metabolism to thermodynamics. This video was created after finishing the first part of the pilot study (the case-study); topics covered by this video were based on students’ misconceptions as revealed from their responses on the pretest.

**Control group.** This group, however, was provided time and a biochemistry textbook to prepare for the posttest. I decided to include a control group to minimize the possibility that the progress students made on the posttest was because of their progress in the course or because of the time interval between the pretest and posttest. Also, by having this control group, I reduced the probability that students made progress in the posttest because they had seen the questions for the second time and they had memorized what was given in the pretest (i.e., testing effect). To ensure the experimental group did not get an educational advantage over the control group, a handout of the information covered by the video was provided to the students from the control group after finishing the study. I discussed with them the mistakes they had made on the test, provided them with some explanations, and answered any questions they had on the open-response test. A posttest including the same questions as the pretest was given during the final
interview two weeks after giving the pretest to all of the groups. Figure 6 shows an overview for this quantitative phase of the pilot study.

![Experimental Design](image)

**Figure 6.** An overview of the quantitative research design.

**Dissertation**

Phenomenology was the philosophical stance used to obtain a deep insight and focus on every particular participant since not every participant would hold the same misconception. Specifically, I sought to find if students used the same terminology from the video during the interview or came up with their own terms. This process helped me find out if they explained their answer through the lens of their own pre-concepts or not. This phase included the use of a learning styles concept inventory called the OSIVQ (Blajenkova et al., 2006) as shown in Appendix E. The use of this inventory allowed me to categorize the students according to their learning styles so interpreting the data was
more valuable since it provided information about who benefitted more from the use of the video.

**Class Observations**

Several observations were made to ensure participants from the course SES626 were an appropriate fit for this study. I was engaged in the class with the students and participated with various class activities that took place during my visits so as to not leave a negative impression on students. Numbers of students attending lectures were compared to the numbers of enrolled students to measure the attendance rate for the course. This information was helpful for me to comment on the setting and these observations were essential to evaluate whether the information covered by the lecture was relevant to this study. The class observations indicated to me that the selected course was suitable for the dissertation and the materials covered were relevant to the concepts targeted by the study.

This course was lecture-based and the class met on-campus regularly for one hour three times a week in a technology classroom. The instructions mainly were given in PowerPoint slides; the chalkboard was sometimes used for further explanations. Glycolysis was covered using chemical structures and enzymes were shown on the reaction arrows in the figures used. The term $\Delta G$ was used excessively, and it was introduced to the students during the first weeks of instruction. In addition, some visual representations were used and explained by the instructor. Since the study targeted glucose metabolism specifically, the observations were made during the week when glycolysis was being covered.
This SES 626 class consisted of 23 students who were enrolled in this course, and 21 students attended when the three observation sessions were made. Student discussions were facilitated by the instructor and group presentations were discussed and prepared by students in class. Online tests were used as an assessment tool for this course. After observing the class three times, I asked for volunteers to participate in the study. These observations were helpful for the study—not only to determine if the class could be used for data collection but it also introduced me to the materials covered by the lecture. For example, the units used for $\Delta G$ by the textbook and by the instructor were kCal/mol while the units used by the open-response test for the dissertation (Appendix F) were in kJ/mol. This could have caused confusion for the students, but I told them about the conversion factor so they could visualize the number for $\Delta G$ and understand its meaning. Without my observations, this discrepancy would have been a source of confusion.

**Recruitment**

I sought volunteers by asking permission from the instructors of the target courses and scheduling a number of visits. I sought participants from the CHEM582/482 course but, unfortunately, none of the enrolled students chose to participate in this study. The enrollment rate of CHEM482 was low (five students) where the capacity of this course was 30 while CHEM582 had only one graduate student taking it when its capacity was 10 students. I did not make any observations in this course and this might have contributed as well to the null response rate in addition to the low enrollment rate.

The capacity for the SES626 course was 25 students (actual enrollment was 23) and nine of them participated in this study. E-mails were sent to the instructors asking permission for class observations and for seeking volunteers. Participation was voluntary
and confidential, and students’ grades were not affected by whether they participated or not. I asked the students who participated to pick a nickname to protect their identities. These nicknames were used in both the recordings and the digital data stored on the computer to protect participants’ identities. There was no link between students’ real names and their pretest or posttest scores.

Two graduate students with developing expertise in the areas of biochemistry and general chemistry were invited to participate in the dissertation. Criteria for choosing these two students were the graduate student must not have participated in the pilot study and must have taught biochemistry or general chemistry laboratories for at least one academic year. They were contacted in person and both were willing to participate. The graduate student whose major was biochemistry was referred to as Grad-Bio, while the other graduate student was denoted as Grad-Gen to account for his general chemistry expertise. Grad-Bio had a GPA of 3.0, and he took advanced biology and biochemistry courses including a course on toxicology. Grad-Gen, however, had a GPA of 3.7 and took only entry-level biochemistry and general chemistry courses.

A purposeful sample of 11 participants took the demographic questionnaire. The OSIVQ (Blajenkova et al., 2006) was then administered to measure students’ differences in visual imagery preferences. The students then took the open-response test for the dissertation (see Appendix F) as a pretest. Two weeks after taking the pretest, students were shown the video, which was different from the one used in the pilot study in that it was not continuous (i.e., segmented).

A semi-structured interview was conducted after each segment and a sheet of paper was provided to the participants for them to answer the questions shown on the
video and give more explanations if needed. The participants were then given a posttest that contained the same questions from the open-response test for the dissertation (see Appendix F). This test was given to check if the misconceptions, if any, still existed. This posttest was given right after they had finished answering the interactive questions that appeared on the screen after each segment of the video. This allowed me to compare students’ posttests to their own pretests since the responses were different from one student to another. Finally, I interviewed the participants to analyze their perceptions to the video. The participants were asked about the origins of their misconceptions if any were found. Appendix E shows the semi-structured questions used in this interview.

Data Analysis

Pilot Study

Data from the pilot study were collected after obtaining approval from the Institutional Review Board (IRB; see Appendix H). The first research question (Q1) was answered by the students’ responses on the interview questions when I asked them to show how they came up with their answers. This stage included a qualitative approach (a case-study). Each item in the open-ended test represented a factor that might influence students’ understanding of metabolism; each item represented a different area such as thermodynamics. Codes such as misconceptions and lack of knowledge were found. I then divided the themes into sub-factors to understand why that particular participant developed such a misconception (misconceptions or pre-concepts). Thus, these sub-factors reflected the origin of misconceptions if it was a school-made misconception or a pre-concept.
For the quantitative part, the data were analyzed using SPSS (version 25); the analysis was run including descriptive statistics. Mean and standard deviation values for the pretest and posttest scores were used. An ANOVA repeated measures at the 95% level of significance (alpha = .05) was run. The assumption of independence was tested along with tests for normality and homogeneity of variances. Cronbach’s alpha was used as a measure of reliability for this research. Pretest and posttest scores were the dependent variable in the ANOVA repeated measures at the 95% level of significance (alpha = .05). The assumption of independence was met since each group was given a different treatment. However, diffusion across groups still violated this assumption. It would be hard to ensure if students from the control group did not contact fellow students from the experimental group about the treatment.

The second and third research questions (Q2 & Q3) were answered through a comparison of the mean scores of the pre/post open-ended-tests using ANOVA repeated measures at the 95% level of significance (alpha = .05). Independent variables were students’ prior knowledge, gender, and treatment type. The levels of these independent variables were as follows: two groups of high and low prior knowledge, two groups of males and females, and the treatment type—either treatment or control. The minimum sample size needed in the current study was 134 participants as determined by G-power (3.1), a software used to determine the power of statistical tests such as t- and F-tests (Faul, Erdfelder, Lang, & Buchner, 2007). The sample size was based on a target power of .80, alpha = .05, effect size = .30, and eight cells for an ANOVA repeated measures analysis. The eight cells were based on levels of the three main independent variables.
Dissertation

Data collection procedures for phenomenological studies involve in-depth and multiple interviews. Other forms of data are also collected such as observations, documents, or artifacts. These procedures involved transcribing and going through the interviews to highlight significant sentences to be used as direct quotes to provide a general understanding on how the participants experienced a phenomenon. In the interpretation phase, the inquirer develops clusters of meaning from these quotes into themes. Creswell (2013) wrote that in phenomenology, the inquirer can simplify the data collection process by including only single or multiple interviews with individuals. The type of sampling is usually purposeful where the inquirer selects participants because they experienced a shared phenomenon with other individuals (Creswell, 2013, p. 80).

Qualitative data from the pilot study and the dissertation were analyzed using thematic analysis (Braun & Clarke, 2006). QSR International’s N-vivo 12 was used to transcribe the students’ interviews and some quotes and artifacts were used to draw the final conclusion (Given, 2008). Qualitative data from the final phase, the survey questions in Appendix E, were used to justify the effectiveness of the treatment. Students expressed their attitude toward chemistry and how they perceived the video. Trustworthiness was assured by the interviews that followed the pretest where students were asked to confirm the answers they wrote on the test.

Concluding Paragraph

This chapter summarized the methodology used in both the pilot and the dissertation studies. In summary, the results of the pilot study were used to enhance the design of the dissertation. Specifically, the mixed methods design of the former was
changed to a qualitative design based on the principles and procedures of phenomenology. Chapter IV provides the results and findings for both studies. Chapter V concludes this dissertation by discussing the results with respect to previous relevant studies and the theoretical framework (see Chapter II).
CHAPTER IV

RESULTS

The results of the pilot study, as described below, were used to revise the research design of the dissertation. First, the results from the mixed-methods pilot study were summarized, and then the qualitative results from the dissertation study were described. The results of the pilot study answered Research Questions 1, 2, and 3. The results of the dissertation study focused mainly on answering Question 4, while the results from Question 1 were expanded based on this qualitative study.

Results of the Pilot Study

Qualitative Results

The case-study was the first phase of this research. It focused on exploring students’ misconceptions as well as distinguishing the hard areas that might need more attention when teaching metabolism. This phase was helpful because it involved engaging graduate chemistry major students in this study; their comments about how hard some questions were or what was the answer they were looking for were helpful in designing the instrument and rewriting the questions for the final phase. The first research question was answered by the students’ responses on the interview questions when I asked them to show how they came up with their answers. This included a qualitative approach (a case-study). Each item in the open-response test represented a factor that might influence students’ understanding of metabolism. Codes such as misconceptions and the lack of knowledge were found. Also, these codes reflected the
origin of some common misconceptions and every item represented a different area such as thermodynamics. Then, I divided the themes into sub-factors and that allowed me to understand why that particular participant developed such a misconception.

Since some misconceptions were revealed after the in-depth interviews with the graduate students, I assumed these misconceptions might be held by undergraduate students as well. When one graduate chemistry major participant was asked to determine if reaction A in the open-response test (see Appendix D) was exothermic or endothermic, she replied, “The reaction was endothermic since in laboratories, we need to input heat to burn glucose.” This wrong explanation revealed a serious misconception about the energy of activation. Suits (2016) wrote that even if the reaction was exothermic, it might need a “spark” to initiate the reaction (p. 41). This student seemed to confuse Gibbs’ Free Energy with the energy of activation and seemed to assume all of the exothermic reactions were spontaneous. Another misconception found by this study was the free-energy change of a reaction depended on its path and how many steps were involved. When a participant was asked if free energy would be the same for reactions A and B, the student said, “No, they would be different since one reaction occurs in vivo, and the other in vitro even if the substrate concentrations were the same.” One graduate student used the term *charge* when describing the oxidation state of carbon. Misuse of this term was serious because it could lead to the development of a vast array of misconceptions, especially when it was used by teaching assistants. That might cause a large spread of this wrong terminology among undergraduate students. Last, one student referred to the molecule “Acetyl-CoA” as “citric acid”; that might be due to the name of the entire pathway, the citric acid cycle, which started with this molecule. This last term
might not be as important as the other wrong terms used by the participants. However, it still would have an impact on their teaching if they needed to use these terms in classrooms, which could generate misconceptions among entry-level undergraduate students.

Themes were found among participants from the concurrent study (the second phase of the pilot study). All of the participants in this stage of the study were undergraduate non-chemistry major students who took two years of general chemistry courses with corresponding labs (CHEM111 and CHEM112) and were currently taking Sport and Exercise Science courses mentioned in the methodology chapter of this dissertation. Students’ responses on the open-response test for the pilot study (see Appendix D) suggested students struggled in understanding general chemistry concepts including oxidation, Gibbs’ free energy, and Le Chatelier's principle. The following six themes were identified: wrong responses due to the lack of knowledge (misinformation), misconceptions, understanding biochemistry concepts, the origins of these misconceptions, the wrong terminology used by the participants, and pre-concepts. The students seemed to misunderstand some general chemistry concepts either by developing misconceptions on them or by not answering the questions correctly due to the lack of information about this particular area. Even if the student was a non-chemistry major, the student tended to use terms such as “pH” or “reduction” when they explained their answers. This meant that understanding chemistry terms and concepts was essential even for non-chemistry major students since they were using them in the interview as well as in their courses. In addition to the topics discussed above, the students seemed to be confused on thermodynamics. This topic is particularly vital not only in teaching general
chemistry but also when teaching metabolism and the energetics of metabolic pathways. Sreenivasulu and Subramaniam (2013) wrote the topic of chemical thermodynamics is known to present learning difficulties among students and that might be due to the abstract nature of thermodynamics expressed mathematically. Learning thermodynamics also involves abstract reasoning that can disagree with logical sense or not comprehended (Sreenivasulu & Subramaniam, 2013).

**Wrong responses due to lacking information.** Not all of the wrong responses were classified as misconceptions in this study. Sometimes students clearly said they did not know, or they guessed the answer and could not show how they came up with it. These wrong responses were categorized under this theme. The undergraduate participants seemed to struggle in understanding Le Chatelier's principle. Item eight on the open-response test (see Appendix D) showed the conversion of malate to oxaloacetate. This reaction belonged to the citric acid cycle (Krebs’ cycle). When the students were asked what effect pH would have on this reaction, all of the undergraduate participants provided the wrong response—pH had nothing to do with this conversion. This question was written in biochemistry context and might have been why none of the participants recognized the general chemistry behind this question. If Le Chatelier's principle was applied to this reaction, the reversible reaction direction was predicted. The reaction favored the reactants side if more hydronium ions were present in the system.

Furthermore, when students were asked to circle one hydrogen atom that would be captured by the molecule NAD⁺, they seemed to be unaware of the proton versus hydride ion. Most of the participants failed to distinguish the hydride that was attached
directly to the malate ion and the proton that was attached to the oxygen in the hydroxyl group. All of these wrong responses were not categorized as misconceptions since they were a result of the students’ background knowledge and, hence, they were categorized as “lack of knowledge” or “mis-information.”

**Misconceptions.** The in-depth interviews revealed if wrong responses were accompanied with common misconceptions and whether or not these misconceptions could be categorized as pre-concepts. One area that students struggled to understand was oxidation and reduction reactions (REDOX). One participant said, “Reaction A is redox because oxygen is involved in the reaction.” Herein lay a famous misconception. Most of the students limited the oxidation process to the presence of oxygen gas and that might have been due to the use of the term “oxidation.” This misconception was mentioned by MacLaren and Morton (2012, p. 45). One might say one definition of oxidation included oxygen. However, students understood that improperly. For example, when reacting chlorine gas with a bromide ion, students who held this common misconception would categorize this reaction as a non-REDOX reaction just because oxygen was not there in the equation on the reactants side. Once the undergraduate participants saw the oxygen gas on Reaction A, they categorized it as a REDOX reaction and then failed to support how they came up with this answer using any other way. I asked them if they were missing any specific information so I could provide them with that information. For example, I asked them if they needed the oxidation states of carbon atom in the reactant and the product to best answer the question. They said no more information was needed for them to answer this question.
**Understanding biochemistry concepts.** The main general research question that guided this research was whether biochemistry students developed a deep understanding of concepts that impacted their learning and if they applied this knowledge to learn biochemistry. One of the important topics on biochemistry is the regulation of metabolism. To master this concept, we hypothesized students needed to be aware of the interconnection between all of the metabolic pathways in addition to understanding Gibbs’ Free-Energy for these reactions. The flat representation for glycolysis assumed all the reactions had the same energy. Students seemed to memorize the control points that regulated all the pathways without understanding them. Since the energy of these reactions was not equal, high energy molecules were used to derive some reactions in a specific direction. Students tended to memorize the steps as ATP was used and assumed these reactions were the control points. One student marked reactions (1, 3, 7, and 10) in the glycolysis pathway to be the control points because of the presence of ATP on the reaction arrow (see Figure 7). Reaction 7 was not one of the control points for the glycolysis pathway. Figure 8 shows the student’s response about choosing this answer. The student seemed to be aware that in some reactions ATP was consumed and in the other reactions ATP was formed. However, knowing this fact was not enough for the student to answer the question the right way. The student reflection on this answer suggested the student used root learning without a deep understanding.
Figure 7. Item 7A on the open-response test for the pilot study.
The origins of misconceptions revealed. When I analyzed the students’ responses, I tried to come up with a conclusion regarding why the students in this study held a particular misconception. One important concept in thermodynamics is energy of activation and one common misconception regarding this concept was “Breaking the bond, generates energy.” This misconception was not studied in the pilot study but I studied students’ understanding of the meaning of energy of activation. Participants in the pilot study confused the concept of reaction spontaneity with activation energy. Participants who answered this question incorrectly thought that since a particular reaction was exothermic, no energy of activation was needed to initiate this reaction. Based on this misconception, one participant categorized the oxidation of glucose to be endothermic process since energy should be input to burn glucose in laboratories. Applying information that was partially true was another source of misconceptions. For example, the student’s response on Figure 7 above showed the student knew controlling glycolysis was related to ATP. However, his answer did not change based on the fact he mentioned in his response on Figure 8. He then seemed to memorize that ATP was related somehow to controlling the glycolytic pathway without a deep understanding.
Knowing part of the information could lead students to make up the other half on their own.

**The wrong terminology used by the participants.** The think-aloud interviews with the participants revealed many wrong terms used by the students interchangeably. For example, the symbol (s) shown on equation A, which represented the glucose state of matter, was read by one of the participants as “salt” instead of “solid.” This was an incorrect use of this term because the term salt could be solid or aqueous. Another student used the term “charge” interchangeably with the term “oxidation state,” which seemed to cause a huge misconception about oxidation (i.e., the molecules shown on Figure 9 were uncharged and hence no electron transfer or oxidation occurred). Another term used in a wrong way was the concept of “equilibrium.” Many students referred to the double headed arrows as equilibrium instead of using the term “reversible reaction.”

![Figure 9](image-url)

*Figure 9.* Item 2 on the open-response test for the pilot study.

**Pre-concepts.** The wrong ideas students said during the interview were classified as misconceptions, pre-concepts, or lack of knowledge. An example of the pre-concepts was substituting the term salt with solid when referring to the glucose state of matter.
This improper usage of this term must be a pre-concept. I assumed any instructor would never use these two terms interchangeably.

**Quantitative Results**

The second research question was answered by comparing the mean scores of the pre/post open-response tests using ANOVA repeated measures at the 95% level of significance (alpha = .05). The independent variables were prior knowledge, gender, and treatment type. The levels of these independent variables were as follows: two groups of high and low prior knowledge, two groups of males and females, and the treatment type—experimental or control. The dependent variables in the pilot study were the scores of the pretest and the posttest and it was a continuous dependent variable. The reliability for the scores on the test was moderate (Cronbach's alpha was .80). The quantitative part of the pilot study was analyzed using SPSS (version 25); the analysis was run including descriptive statistics (see Table 1).

The assumption of independence was met. Each group was given a different treatment. However, diffusion across groups still violated this assumption. Tests for normality and homogeneity of variances were run. The Shapiro-Wilk test indicated the data were approximately normally distributed (p > .05).
Table 1

Descriptive Statistics and Main Effects for Pilot Study

<table>
<thead>
<tr>
<th>Main Effect</th>
<th>Levels</th>
<th>N</th>
<th>Pretest Scores</th>
<th>Posttest Scores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>M</td>
<td>SD</td>
</tr>
<tr>
<td>Treatment type</td>
<td>Control</td>
<td>21</td>
<td>10.76</td>
<td>3.63</td>
</tr>
<tr>
<td></td>
<td>Experimental</td>
<td>24</td>
<td>9.75</td>
<td>2.86</td>
</tr>
<tr>
<td>Prior Knowledge</td>
<td>Low PK</td>
<td>19</td>
<td>7.90</td>
<td>1.56</td>
</tr>
<tr>
<td>(PK)</td>
<td>High PK</td>
<td>26</td>
<td>13.42</td>
<td>1.92</td>
</tr>
<tr>
<td>Gender</td>
<td>Female</td>
<td>36</td>
<td>10.36</td>
<td>3.42</td>
</tr>
<tr>
<td></td>
<td>Male</td>
<td>9</td>
<td>9.67</td>
<td>2.50</td>
</tr>
</tbody>
</table>

The control group consisted of 21 students and the treatment group had 24 participants. The assignment was random and there were 36 females and only nine males. The mean scores for the pretest were 10.76 and 9.75 for the control and the treatment group respectively, and posttest were 10.86 and 13.75 points for the control and the treatment group, respectively. The grade point average (GPA) for the undergraduate participants ranged from 2.6 to 4.0. Table 1 above provides descriptive statistics for the participants in the pilot study with a summary of levels of the main effects.

The results of this phase were promising as there was no interaction among the three independent variables, \( p > .05 \). This allowed for direct interpretation of the main effects: there was a mean difference between the treatment and the control group. The treatment was significant, and it seemed the video used was effective. The video only covered two concepts of the five used in the open-ended test. Questions that represented the other concepts were kept in the posttest to see if the progress students had made after the study was because of the treatment and not because of the exposure to the same
questions for a second time (i.e., testing effect). For example, the concept of oxidation was not covered by the video so if a student missed that question in the pretest, the student would have missed it again in the posttest. That was further evidence the treatment covered the concepts related to chemical potential energy. However, the video held their attention and did not provide the answers directly. The sample size was a limitation and prevented the full interpretations of the results since the power of the test used (ANOVA) was questioned.

The second and third research questions were answered using ANOVA repeated measures. At a significance level of .05, there was a statistically significant mean difference on pretest and posttest scores between the two groups on prior knowledge (high PK and low PK). Strong evidence in the sample suggested the two prior knowledge groups had different means ($p = .000$) with estimate effect size of .50. Evidence in the sample suggested the video was effective and was associated with an improvement in students’ scores. The ANOVA summary shown in Table 2 suggests a statistically significant treatment type effect existed in the sample with no interactions among the treatment type and the other factors. However, no statistical mean difference was found between the two groups of males and females in this study; this might have been due to the unequal representation of the gender groups ($n_{\text{males}} = 9$, and $n_{\text{females}} = 36$).
Table 2

Analysis of Variance (ANOVA) Summary Table

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Mean Square</th>
<th>$F$</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>1</td>
<td>6368.062</td>
<td>897.076</td>
<td>.000</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>40.817</td>
<td>.5750</td>
<td>.022</td>
</tr>
<tr>
<td>Prior Knowledge</td>
<td>1</td>
<td>287.307</td>
<td>40.473</td>
<td>.000</td>
</tr>
<tr>
<td>Gender</td>
<td>1</td>
<td>.875</td>
<td>.123</td>
<td>.727</td>
</tr>
<tr>
<td>Treatment * Prior Knowledge</td>
<td>1</td>
<td>.954</td>
<td>.134</td>
<td>.716</td>
</tr>
<tr>
<td>Treatment * Gender</td>
<td>1</td>
<td>.015</td>
<td>.002</td>
<td>.963</td>
</tr>
<tr>
<td>Prior Knowledge * Gender</td>
<td>1</td>
<td>1.386</td>
<td>.195</td>
<td>.661</td>
</tr>
<tr>
<td>Treatment * Prior Knowledge * Gender</td>
<td>1</td>
<td>5.195</td>
<td>.732</td>
<td>.398</td>
</tr>
<tr>
<td>Error</td>
<td>37</td>
<td>7.099</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Both students from the low and high prior knowledge groups benefitted from the treatment (see Figure 10). The scores for the pretest and posttest were plotted for both groups of prior knowledge. In summary, the results of this pilot study were used to enhance the design of this dissertation including the research design that changed to qualitative research to get more in-depth information about the participants and their conceptual understanding to the topics covered by this study. The video seemed to be effective and thus it was given as a treatment for the participants in this dissertation.
Dissertation Results

Demographic Variables

All of the participants in the dissertation were graduate students and only two of them were chemistry-major students; there were five males and six females. Table 3 shows students’ majors, nicknames they picked, and their OSIVQ (Blajenkova et al., 2006) scores. According to the scores shown in Table 3, some participants were either visualizers, spatial visualizers, or showed no strong preferences to any category. The OSIVQ scores were based on the categories shown below, which were developed by Hilsenbeck-Fajardo’s dissertation (2009) and modified by Kozhevnikov et al., (Blajenkova et al., 2006; Blazhenkova, & Kozhevnikov, 2009).

Figure 10. ANOVA profile plot for the participants in the pilot study.
• Strong preference: 3.5 to 5
• Moderate preference: 3 to 3.4
• No preference: 1 to 2.9

As shown in Table 3, four participants were classified as object visualizers (Grad-Gen, Starfish, Elisabeth, and Tree), while two were spatial visualizers (Grad-Bio and Sally). One participant (Lowry) indicated a preference for both spatial and object styles. None of the participants were classified as being a verbal learner since none of them expressed a preference for the verbal learning style based on their OSIVQ scores. All the participants were white except of Elisabeth; she was Filipino. Most of the participants reported having good to excellent attitude about chemistry; Molly was the only participant who mentioned that her attitude towards chemistry is not good. The grade point average (GPA) for the participants ranged from 3.2 to 4.0.
Table 3

Students’ Demographics and Object-Spatial Imagery and Verbal Questionnaire Test Results

<table>
<thead>
<tr>
<th>Score for Each Category</th>
<th>Gender</th>
<th>Major</th>
<th>Student Nickname</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>Verbal</td>
<td>Spatial</td>
<td></td>
</tr>
<tr>
<td>3.80</td>
<td>2.47</td>
<td>3.93</td>
<td>M</td>
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<td>3.27</td>
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</table>
Thematic Analysis

Ideas and patterns found across data are summarized in Table 4. These themes categorized three different goals of conducting this research: what misconceptions students held, what the origins of these misconceptions were, and how to improve students’ conceptual understanding of metabolism.

Table 4

*Themes and Corresponding Goals*

<table>
<thead>
<tr>
<th>Themes</th>
<th>Goal/Purpose or Research Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wrong responses</td>
<td></td>
</tr>
<tr>
<td>Misconceptions</td>
<td>Q1: Misconceptions students have?</td>
</tr>
<tr>
<td>Origins of these misconceptions</td>
<td>Q1: Origin of these misconceptions?</td>
</tr>
<tr>
<td>The interview effect</td>
<td>Q3: How to improve students’ conceptual understanding?</td>
</tr>
<tr>
<td>Effect of the energy profile diagram</td>
<td></td>
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<tr>
<td>Student’s experience with the video</td>
<td>Q4: How students perceived the video.</td>
</tr>
<tr>
<td>Use of more scientific terms after watching the video</td>
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</table>

Wrong responses. In this study, I distinguished between two related terms: students’ misconceptions and their wrong responses. That is, not all wrong answers were considered to be misconceptions. The criteria of identifying misconceptions were based on the in-depth interview with the participants. Specifically, if the participant seemed to provide the same wrong response several times, then it was scored as a misconception for
this study. Also, it was a “misconception” if it had been cited in the literature as being a common misconception. In this study, many misconceptions were exposed even without asking specific questions designed to trigger them. An example of a wrong response is shown in Figure 11. This figure showed a wrong response regarding the difference between hydride and proton. Grad-Gen chose the proton attached to the oxygen in the hydroxyl group to be the hydride that was captured by NAD$. Another example of wrong responses is shown on Figure 12 by the same student—Grad-Gen. Grad-Gen predicted several values for $\Delta G$ for reactions A, B, and C. Unfortunately, he did not relate these values together since the values he suggested did not add up to give the one he predicted for reaction C. Answering this question incorrectly was not scored as a misconception but as a wrong response.

5. In the reaction below, one H atom from the malate molecule is captured by the NAD$^+$ molecule.

![Chemical reaction diagram]

Figure 11. Grad-Gen response regarding difference between hydride and proton.
3. Draw the energy diagram for the reactions shown below.

A. \( \text{ADP} + \text{PO}_4^{2-} \rightleftharpoons \text{ATP} \)

\[ \Delta G = +14 \text{ KJ/mol} \]

B. \( \text{phosphoenolpyruvate} \rightleftharpoons \text{pyruvate} + \text{PO}_4^{2-} \)

\[ \Delta G = -23 \text{ KJ/mol} \]

C. \( \text{ADP} + \text{phosphoenolpyruvate} \rightleftharpoons \text{ATP} + \text{pyruvate} \)

\[ \Delta G = +14 \text{ KJ/mol} \]

*Figure 12.* Grad-Gen response on the concept of coupling reactions.
**Misconceptions.** Table 5 provides a summary of misconceptions found among both chemistry and non-chemistry majors who participated in this dissertation.

Specifically, both chemistry and non-chemistry majors held the first misconception list, while only the non-chemistry majors possessed the remaining misconceptions.

Table 5

<table>
<thead>
<tr>
<th>Misconception</th>
<th>Students Who Held It</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Oxidation processes cannot occur in anaerobic conditions; the presence of oxygen is necessary for oxidation.</td>
<td>Only non-chemistry majors.</td>
</tr>
<tr>
<td>3. Oxidation is the loss of carbon atom.</td>
<td>Only non-chemistry majors.</td>
</tr>
<tr>
<td>4. At higher pH, the concentration of hydronium ions is greater.</td>
<td>Only non-chemistry majors.</td>
</tr>
<tr>
<td>5. Adding a catalyst will affect reaction thermodynamics.</td>
<td>Only non-chemistry majors.</td>
</tr>
</tbody>
</table>

All 11 participants, regardless of their majors, confused the ATP hydrolysis with the process of breaking the bond of ATP (Misconception #1). Breaking the bond in ATP is the first step in ATP hydrolysis. The hydrolysis of ATP is an exothermic process while breaking the bond in ATP in the first step is not. All of the participants responded to this question by saying that breaking the bond in ATP generated energy, which was considered a common misconception based on literature (Mills & Sweeney, 2007).

Figure 13 shows a screen-shot of the video where the participants were given a question
in the video regarding this concept and that was after a brief introduction to exothermic and endothermic processes. Since both graduate chemistry major students answered yes in response to the question shown on Figure 13, this was scored as a misconception. Regarding this question, Grad-Gen said, “Yes, and that is a part of how your body drives this chemical reaction or drive certain mechanisms through ATP, and so it's typically regarded as a spontaneous reaction. As what helps make otherwise less favorable reactions more favorable.” The second graduate student, Grad-Bio, said,

Yes. It does. So energetically speaking the more bonds you put together between electronegative atoms being the phosphate groups, generates more and more repulsion between them and that means more and more energy is required in order to form these bonds. And so, if you are to break one of these bonds it would be favorable to do so because the amount of energy that is used to hold that bond together is actually lower than the amount of energy that the phosphate group is trying to push against each other to release each other. However, because of that whenever you do hydrolysis of it, you are releasing the amount of energy that is needed to overcome that repulsion within that bond.

Sally, a non-chemistry major, as well responded to this question in the same way where she confused the hydrolysis of ATP with breaking its bond:

Breaking the bond in ATP does generate energy. There is energy held in the bond between ATP and the phosphate group and once you break the bond, energy will be released. ATP has a higher free energy that ADP does. So, if you take ATP to ADP then whatever the difference in free energy is how much free energy you are releasing.
Sally and another graduate student, Molly, answered this question incorrectly; they had confusion with the term “generates” and suggested using another term such as “transferred or released” when talking about energy. Appendix I shows screenshots of the multimedia video, and a transcription of the video is provided in Appendix J (Voet et al., 2013).

In most cases, the energy required to drive endergonic reactions comes from ATP hydrolysis, by which cells break down ATP to use its energy.

Does breaking the bond in ATP generate energy?

Explain your answer using the energy profile (reaction coordinate diagram).

Figure 13. Screen-shot from the video showing the question about ATP hydrolysis.

The results from the pilot study showed non-chemistry major students limited the oxidation processes to the presence of oxygen (Misconception #2). To explore if this misconception was widespread, I investigated if the participants in the dissertation held the same misconception. When Lowry, a graduate student majoring in biomechanics, was asked if there was a net oxidation of substrate carbon atoms in glycolysis, he said there was oxidation; however, he changed his response during the interview.

Researcher: Is glycolysis aerobic or anaerobic?
Lowry: Oh, I guess glycolysis would be considered anaerobic. I guess there is no net oxidation of the substrate carbon atoms, but it would be a release in free energy.

Researcher: Just to clarify, since glycolysis is an anaerobic pathway, you said there would be no net oxidation of carbon atoms.

Lowry: Yes, if it is anaerobic, there would be no net oxidation of carbon atoms.

Researcher: So, you link oxidation with the presence of oxygen?

Lowry: Yes.

Researcher: And if there is no oxygen in the surrounding, there will be no oxidation reactions?

Lowry: Yes. There cannot be. No oxidation.

Elisabeth, an exercise physiology graduate student, had the same belief as Lowry. She defined oxidation and reduction correctly: “Redox reactions where there is gaining and giving up electrons.” However, when it came to applying this definition, she had hard time doing so. She categorized glycolysis to be an oxidative pathway but she failed to support her answer. Elisabeth not only had the misconception that oxygen must be involved in oxidation but she confused oxidation with giving up carbon and not electrons (Misconception #3). Since carbon dioxide is lost during the Krebs’ cycle but not glycolysis, Elisabeth categorized glycolysis to be a non-oxidative pathway.

Researcher: Do you categorize glycolysis as an oxidative pathway?

Elisabeth: Yes.

Researcher: Can you give me a reason for that?
Elisabeth: Yeah well, yes because in part of glycolysis you are losing CO₂ molecules and using your oxygen so it is complicated.

Researcher: In glycolysis there is no loss of carbon substrate

Elisabeth: True

Researcher: There is no oxygen involved at all, so can you still say glycolysis is an oxidative pathway?

Elisabeth: No, doesn’t use oxygen and doesn’t lose any carbons.

Another misconception revealed by this dissertation was exothermic reactions do not require catalysis and if a catalyst would be used, an endothermic reaction would become exothermic (Misconception #4). This misconception was held by two non-chemistry major graduate students. Lowry said, “If free energy is negative, you do not need to catalyze this reaction and makes it to occur.” This misconception was common among students and it showed students who held this misconception did not develop the proper scientific understanding to both thermodynamics and chemical kinetics.

Catalyzing a chemical reaction increases the reaction rate by lowering the energy of activation needed for a reaction to occur and that will not change Gibbs free-energy for that reaction (Bak & Schousboe, 2017). Elisabeth held the same misconception: “There are enzymes in different reactions that can change the ΔG to make it more favorable.”

Another pre-concept was found that at higher pH, the hydronium ion concentration is higher (Misconception #5). It was common finding among the non-chemistry major graduate participants. This confusion must be internal (a pre-conception rather than a misconception) and because neither the textbook nor the instructor was responsible for this confusion. Fortunately, the participants tended to self-correct
themselves during the interview. The question asked the effect of pH on the reaction provided on item 5 on the open-response test for the dissertation (see Appendix F) while it was showing the hydronium ion instead. That might have involved more than a step, and this could have been the source of their confusion about this question. The students did not notice the difference between the hydronium ion and the pH; hence, they confused the two concepts.

**Origins of these misconceptions.** Unlike the pilot study, in the dissertation, I gave the participants the chance to suggest possible origins of their misconceptions, thus eliminating researcher bias. Molly and Sally thought breaking the bond in ATP would generate energy; they were confused about the term “generate” and suggested using another term such as “transferred or released” when talking about energy. They said the use of this term confused them. Many participants said that in their textbook, they used to see only the value of ΔG for the overall reaction; they had not thought about ΔG for coupled reactions to be before and after the coupling process. They said they only focused on the final ΔG value given at the end of every reaction. Both participants said they learned the correct concept in high-school but the word “generate” confused them. However, when it came to applying the knowledge they received in high-school, they failed transferring that knowledge to a new setting. Mills and Sweeney (2007) wrote that using phrases such as “the high energy bond in ATP” and “the energy stored in the bond” was the source of this misconception. Instead, the discussion should have included chemical potential energy (Mills & Sweeney, 2007).

Another student wondered why the term of reduction was used when it came to gaining electrons. He said this had been a source of confusion for him for several years.
I also wondered why the term oxidation was used and was not updated when the oxidation definition was updated several times. Oxidation is not limited to the presence of oxygen so maybe incorporating the element oxygen in the name of the process of oxidation caused this confusion.

The only misconception chemistry major students had was breaking bonds generates energy. A follow up question about the origin of that misconception was asked to which Grad-Bio replied:

I think the origin of this misconception at least for me is that in all the times I have been taught about it, you were usually not asked in a sort of way to how you add energy to it before it breaks, you talking most of the times about the overall reaction so you end up with this misconception where you connect it breaking with it making the product. So, if making the product generates energy, then breaking the bond must generate energy whereas in reality, breaking that bond is releasing that energy, you are not making it with the break, you are allowing the energy to be generated afterwards. I feel that a misconception comes from how we were taught this as an overall reaction as supposed to be initial, add energy to it, breaks, the resulting products are lower in energy. Perhaps, if we found a way to make this clear for our students that the energy is going into first, then it is breaking, then the act of those molecules breaking a part until lower energy levels release energy. I think that will make it a little clearer.”
Improving Students’ Understanding of General Chemistry Concepts That Impact Biochemistry

The Interview Effect

Interviews with students helped clarify some terms and concepts used inappropriately before the interview. For example, during the interview, many students changed their responses to more appropriate ones. Elisabeth said enzymes could make non-favorable reactions occur and this misconception was confronted by giving her an example from glycolysis:

Researcher:  Lets choose reaction number 3 on glycolysis. So fructose-6-phosphate converted to fructose-1,6-bisphosphate by adding an ATP to this reaction, you said that the enzyme will make it favorable so in this case is it the enzyme phosphofructokinase made this reaction proceed in the forward direction or the presence of ATP that converted to ADP?

Elisabeth: It’s the presence of the ATP that allowed it to happen so it is not necessarily an enzyme that could move it forward.

This misconception seemed to be robust since she still held to the idea that a catalyst would drive the reaction in a forward direction. This concept related catalysis to the chemical kinetics in addition to thermodynamics. It seemed that students struggle in these chemistry concepts and they were all related to one key concept: the energy profile diagram.
Effect of the Energy Profile Diagram

Another factor that contributed to improving students’ conceptual understanding was the use of the energy profile diagram. Participants were asked to draw the energy profile diagram for ATP hydrolysis after they had seen introductions to exothermic, endothermic, and coupled reactions on the video. Drawing the energy profile diagram helped the participants self-correct their responses on ATP hydrolysis. For example, Sally was asked to show the stage on the energy diagram in which ATP bond breaks. She drew the graph correctly, and she self-corrected herself. That is, she stated that energy is needed to break the bond in ATP up to the stage where the activated complex is formed.

The misconception revealed by interviewing Grad-Bio and Grad-Gen was that “breaking the bond of ATP generates energy.” Both students answered the question regarding this misconception incorrectly and both students changed their answers when I asked them more questions about this misconception. I asked them to use the energy profile diagram to answer this question. For instance, when I asked Grad-Bio to use the diagram, he said: “You have the ATP starting to break apart to form ADP loosely bonded to the last phosphate group. After this point you would break it off and that would end up at a lower energy level than what you were at the beginning.” All of the participants seemed to understand the energy profile diagram and when it was used by them to show how they came up with their answers, they seemed to self-correct themselves and explained the diagram very well.

The last research question, which was how the students perceived the usefulness of this treatment, was answered via a final interview with the participants. All the data
collected from this survey were qualitatively analyzed. The findings were compared with the quantitative data as a way to triangulate the findings via a concurrent research design.

**Student’s Experience with the Video**

Overall, the participants in this dissertation liked their experience with the treatment they received. The posttest was given to them right after an online quiz on the topic of glycolysis. Two participants reported they wished if they had received the treatment before the quiz. They said the video helped them understand the glycolysis pathway better and material covered by the video was relevant to the materials taught in their course. Some participants requested access to the video via the course management system (CANVAS) so they could use it later in the semester. In general, all of the participants liked the experience they had in this dissertation.

All of the participants described their experiences with this video as positive. Grad-Bio said, “It was fairly informative. I feel the questions at the end made it more concrete as far as what you are trying to interpret.” The final interview also targeted any misconceptions students held, where a particular misconception originated, and how instructors could teach students who held similar misconceptions. Grad-Bio said,

I think it could be beneficial towards teaching it. Many students have a hard time connecting lecture which could be just someone talking to them considering, the length of time for actual experiences or actual reactions, and any image read that can be used for it or explanation of it, I feel it is helpful for students to learn.

Regarding helping students learn biochemistry concepts, he said, “We should interpret the energy diagrams for students better and portray it better. Going through this again has refresh my information and I need to go back to see if I have any misconceptions.”
The other participants suggested adding some topics to the treatment or to be studied more by researchers including the pH and enzymes as these topics confused them and were perceived as hard. One participant said enzymes were always one of his main confusion sources and he suggested I add some extra questions about them.

**Use of More Scientific Terms**

The participants exhibited posttreatment improvement. Frequent use of more scientific terms by participants after watching the video was a sign of this improvement. Molly defined the state of equilibrium as the process by which the number of reactants equaled the number of products and she failed to define what she meant by using the term “number.” After watching the video, Molly said, “Equilibrium is when ΔG is zero, so it is not negative or positive.” Another example that showed this improvement was related to the concept of “coupled reactions.” Students had a hard time finding a relationship between reactions (a) and (b) in question 3 of the pretest (see Appendix G). After watching the video, many students showed a better understanding of this concept and used the correct terminology for it. Grad-Bio failed to name the relationship between these reactions but after the video, he used the term “coupled reactions” when describing the relationship between these two reactions.
CHAPTER V

DISCUSSION

The purpose of this mixed-methods research was to identify common misconceptions among undergraduate non-chemistry major students. This chapter includes a discussion of its major findings as related to the literature on improving students’ conceptual understanding of metabolism and implications of these findings. The chapter concludes with a discussion of the limitations of the study, areas for future research, and a brief summary.

Overview

In order to achieve the goal of this dissertation and answer the four research questions, a mixed-methods approach was used in two separate studies. In the pilot study, both the qualitative and quantitative results provided a good foundation for the dissertation study. These results were used to plan and analyze an in-depth dissertation study of the phenomenon of interest. Specifically, a phenomenological approach was used to clarify student conceptions and misconceptions of metabolic pathways.

The pilot study used mixed methods with a sequential exploratory design. First, I used a case-study to scan and explore whether students had any misconceptions regarding the targeted general chemistry topics. Next, a quantitative phase that was part of a concurrent design. This quantitative phase was coupled with a qualitative approach, which was culminated by a final interview. This final interview was the key component
of this research since it involved asking students about how they came up with their answers and their pedagogic perceptions of the video. Based on the results I received from both phases, I edited the questions on the open-ended test and modified the video, in order to enhance its use in my dissertation study.

I focused the qualitative dissertation on studying the phenomenon of student conceptions and misconceptions on the metabolic pathways. Specifically, a phenomenological approach was used to engage as many different majors as possible rather than limiting participations to chemistry major students. This phase included initial, in-depth interviews to examine whether the participants developed a proper scientific understanding or developed misconceptions instead. In addition to these interviews, a final interview was conducted with every participant, after the pretest and posttest, to obtain more information about student’s perceptions about the video. The key component was the in-depth interviews, and the primary source of data came from thematic analyses of students’ explanations. These explanations were then coded and themes were identified.

Many misconceptions were revealed by the first phase of the pilot study (the case-study) and by the second phase, the concurrent study, when I interviewed the participants after they watched the video. These in-depth interviews revealed a number of misconceptions regarding general chemistry concepts such as thermodynamics and oxidation and reduction processes. Students confused the term energy of activation with Gibbs’ free energy. Many participants thought exothermic processes would not require energy to proceed. The students must have thought the term spontaneity of a reaction meant the reaction did not require energy of activation to proceed. Other students
thought Gibbs’ free energy would be affected by the path of the reaction or the mechanism. For example, the exothermic process of glucose oxidation would produce different energy dependent upon whether the conditions were in-vitro rather than in-vivo. Understanding how enzymes work was another source of confusion. Students from the dissertation study thought enzymes could make a reaction more favorable by changing its free-energy change, ΔG, to a more negatively favorable value. This was considered a misconception since an enzyme would not affect the thermodynamics of a reaction. This misconception seemed to originate from their confusion between ΔG and the activation energy of a reaction.

When analyzing the qualitative data for both the pilot and the dissertation studies, it was obvious and easy to distinguish if the wrong responses were due to misinformation or misconceptions. However, no other categorization was done to the correct answers; that is, correct answers could have been the result of a lucky guess or scientific, proper knowledge. More attention was given to the incorrect responses to best serve the research purpose: identify common misconceptions and help students improve their schemas. Huddle and Pillay (1996) wrote that choosing the correct answer did not guarantee that students developed the proper scientific understanding of a phenomenon. They found that students used incorrect reasoning strategies to come up with correct choices (Huddle & Pillay, 1996).

When these misconceptions and hard topics were incorporated in the video, students seemed to understand the general chemistry topics better based on their improvement on the posttest scores. This was the main finding of the second phase of the pilot study, which used the concurrent approach. I chose this approach because of the
need to conduct a quantitative study to validate the instrument used and to ask how students came up with their answers. In this phase, quantitative data along with the qualitative data were collected and analyzed simultaneously.

**Limitations**

This dissertation study added to the literature of using multimedia videos to improve students’ conceptual understanding of chemistry. The improvement students received unfortunately could not be generalized due to the small sample size in the quantitative phase of the pilot study. In addition, in the phenomenological study, all of the participants were either object or spatial visualizers according to the OSIVQ (Blajenkova et al., 2006) scores shown in Table 3. This represented a bias in the sample of participants since no verbal learners were present in this study. This could have impacted the results, especially the last part, which was how students perceived the treatment since visualizers tend to prefer the use of figures and diagrams to visualize concepts and the video included a lot of diagrams.

The qualitative approach I used did not allow me to make strong claims about the effects of the multimedia tool I used to gauge students’ learning gains. Qualitative research always has this limitation. If the dissertation study was accompanied by a quantitative approach, then the results could be interpreted better and generalized. Studies like the current one support using multimedia instructional interventions such as improving students’ attitudes and understanding.

Since the normality assumption was questioned, more tests could be done. It was hard to get the sphericity test when ANOVA repeated measures were used. That might be due to the tests only being repeated twice (first time for the pretest and the second time
for the posttest); at least three-time periods are recommended to get a baseline to compare the two other times.

Although the sample from which data were gathered was small, it could still be possible to provide meaningful findings and interpretations since it matched the existing literature. The results from my pilot study suggested a gain in students’ scores in the experimental group; however, this was not the case for the control group. This difference might reflect researcher bias wherein I unintentionally did not allow for a drop in the scores by using the same pretest. For the posttest, I gave the students their pretests during the interview and asked them if they would like to make any changes. Not all of the participants in the control group changed their answers and, thus, most of their grades stayed the same. This method also limited the probability of using the difference between the pretest and posttest as a dependent variable since using this difference gave a skewed distribution. In the dissertation, students were asked to retake the test using a blank test to see if they would get a different score. However, learning gain was not possible since the difference between the pretest and posttest was not calculated for the dissertation study. This dissertation was qualitative; thus, I did not score students’. This dissertation was qualitative. Another limitation to the pilot study was most of the participants were females. This was probably because the majority of the students enrolling in the target courses were female.

**Linking Theories to the Findings**

The use of the visual aids is often accompanied by cognitive overload. One way I tried to reduce the possibility of students being overload was by adding a narrative to the video in order to help students focus attention on the relevant objects in order to organize
their thinking. Thus, any future study should be associated with a measure of working memory capacity or cognitive overload. In addition, a more thorough description of the participants’ characteristics is needed. Most of the participants in the dissertation were either object or spatial visualizers and all of them liked the video. Lowry and Elizabeth wished they had seen the video before their course exam as it was administered one week before the treatment. Other students suggested the video should be used as a required instructional tool or an optional one so they could have access to it on their courses’ learning portals. This agreed with their learning style preference scores reported earlier and thus matched the principles of cognitive learning theory described in Chapter II of this dissertation.

Having the students watch a video with narratives increased their abilities to store the given information for a longer time according to dual-coding theory. No long-term approach was accompanied by this current research. If the long-term effect of the video used by this study could be studied, then a statement about students’ retention rate would be investigated. The posttest then might be given to the participants right after they took their pretest (on week 1), or a second posttest after a period of time could be given. A single-subject design would be helpful to test the ability of the students from the experimental group to store the information longer than the students from the control group. The single-subject design involves testing students for multiple times when retention rate is a research focus. In addition to this design, factor analysis would be considered an excellent technique to answer two of the main questions raised by this study. These two questions were as follows: where did these misconceptions originate, and what concepts could be considered the most difficult to learn and did they correlate
with the areas where students held more misconceptions? Going back to the main limitations, the sample size needed would be higher than the sample size used for this study if factor analysis was considered.

As discussed in the methodology section, the sample size needed to get a reliable power for the analysis was large. To collect such large amounts of data with this study’s design, studies would need to be done over more than one academic year. If this was the case, different students with different background knowledge would participate and many other factors would probably influence students’ learning gains other than the treatment effect. Thus, the pretest used in the pilot study would not be a sufficient measure for students’ prior knowledge. One way to overcome this obstacle would be to incorporate the questions used in this treatment in the course exams and grade them separately. The video could also be used in their classroom and in this case, all of the students would be in the treatment group. Another section of the same course could be used as the control group. This could produce more reliable data since all of the participants would be evaluated under the same conditions.

**Discussion**

Glucose is the sole metabolic fuel was considered a misconception about metabolism and was found among high school students (Oliveira, et al., 2003). Students thought that ATP production fell during fasting or a low-carbohydrate diet (Oliveira, et al., 2003). Furthermore, students thought that the models used in textbooks depicts what happen in reality inside cells Storey (1991). Most of the previous studies focused on the application of the metabolic pathways. However, the current study focused on chemistry concepts that affected metabolism, and their application on a biochemistry setting. Some
of these concepts are usually taught in general chemistry courses such as catalysis, energy of activation, oxidation, and free-energy; other concepts such as bioenergetics, ATP hydrolysis, and the process of glucose regulation were considered biochemistry topics in this study, and misconceptions regarding these concepts were also targeted.

One of the important topics in biochemistry is the regulation of metabolism. To master this concept, students needed to be aware of the interconnection between all of the metabolic pathways as well as to understand Gibbs’ Free Energy for these reactions based on the assumptions made. The flat representation for glycolysis assumed all the reactions had the same energy. Students seemed to memorize the control points that regulated all the pathways without understanding them. Since the energy of these reactions was not equal, high energy molecules were used to derive some reactions into a specific direction.

Comparing the number of pre-concepts to the number of misconceptions revealed, I questioned the way concepts were taught, i.e., the ways instructors introduced students to thermodynamic variables such as the energy of activation. Was the energy-profile diagram used in non-chemistry courses? Many studies involved the use of student generated drawings to diagnose misconceptions (Karpudewan et al., 2017, p. 35). However, in this dissertation, drawings were used to confront students’ misconceptions (energy profile diagrams). This diagram was used to confront the misconception of “breaking the bond, generates energy.”

Additionally, students were confused about the concept of oxidation. Specifically, the misconception that the oxidation of carbon in glucose is due to the presence of oxygen. That is, students seemed to be unfamiliar with the different oxidation
states of carbon when fully hydrogenated as compared with a carbon that was fully oxidized (see Figure 14). Traditional instruction might be blamed for developing the above misconceptions since they are not considered pre-concepts. This figure was given to the participants after the completion of the study as a handout.

Based on the results I obtained from this dissertation, metabolic reactions should be taught with the aid of energy profile diagrams since the essential topics the participants struggled with were thermodynamics and catalysis. The main common graph using these concepts is the energy profile diagram. However, according to Lamichhane, Reck, and Maltese (2018), these diagrams were still two-dimensional illustrations and considered a simplification of the structural coordinate.

The way many non-chemistry major undergraduate students from the pilot study drew the energy profile diagram on the pretest did not seem random. All of them drew lines instead of curves. All of the participants from the experimental group changed their drawings after watching the video. This systematic, wrong illustration of the curved relationship suggested a systematic emphasis to linear relationships. In many topics in chemistry, converting curved relationships to linear is mandatory for further use of data. Chemical kinetics, Arrhenius equation, and Beer law are examples of reinforcing the importance of linear relationships over curves. Scientists emphasized the use of linear relationships since they are well-studied and values of the slope or R-squared usually have meanings and should be reported with linear equations to be used further.
<table>
<thead>
<tr>
<th>Compound</th>
<th>Formula</th>
<th>Oxidation Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>O=\text{C}=\text{O}</td>
<td>+4 (most oxidized)</td>
</tr>
<tr>
<td>Acetic acid</td>
<td>\text{H}_3\text{C}=\text{C}=\text{O}OH</td>
<td>+3</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>:\text{C}=\text{O}:</td>
<td>+2</td>
</tr>
<tr>
<td>Formic acid</td>
<td>\text{H}=\text{C}=\text{O}OH</td>
<td>+2</td>
</tr>
<tr>
<td>Acetone</td>
<td>\text{H}_3\text{C}=\text{C}=\text{CH}_3</td>
<td>+2</td>
</tr>
<tr>
<td>Acetaldehyde</td>
<td>\text{H}_3\text{C}=\text{C}=\text{H}</td>
<td>+1</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>\text{H}=\text{C}=\text{H}</td>
<td>0</td>
</tr>
<tr>
<td>Acetylene</td>
<td>\text{HC}=\text{CH}</td>
<td>-1</td>
</tr>
<tr>
<td>Ethanol</td>
<td>\text{H}_3\text{C}=\text{C}=\text{OH}</td>
<td>-1</td>
</tr>
<tr>
<td>Ethene</td>
<td>\text{H}_2\text{C}=\text{C}=\text{H}</td>
<td>-2</td>
</tr>
<tr>
<td>Ethane</td>
<td>\text{H}_3\text{C}=\text{C}=\text{H}</td>
<td>-3</td>
</tr>
<tr>
<td>Methane</td>
<td>\text{H}=\text{C}=\text{H}</td>
<td>-4 (least oxidized)</td>
</tr>
</tbody>
</table>

*Figure 14. Oxidation states of carbon (Voet et al., 2013).*
Implication and Future Work

One of the reasons this dissertation was conducted was the lack of research in this research area and the importance of the topics targeted by this study to biochemistry courses as taught to chemistry or non-chemistry majors. In the existing literature, quantitative and mixed methods approaches were valuable research tools and helped construct valid assessments such as three-tier tests and concept inventories. However, a remarkable deficiency was noticed in qualitative studies. Many qualitative studies were missing essential, scientific research features. Some studies were lacking students’ quotes and artifacts and contained only the author’s opinion.

Even when some misconceptions revealed by this dissertation were described in the literature, it was still valuable to recheck if these misconceptions were robust and prevalent. Their frequencies as well could predict how widespread they were. For example, all of the participants in my phenomenological dissertation held the misconception of “breaking bonds generate energy” regardless whether their major was chemistry or not. This was still a valuable finding to report because after years of revealing this misconception, it seemed the instructional methods used today still does not correct this solid network of wrong ideas. Educators should be aware of addressing and introducing misconceptions to their students and try several ways to find the proper teaching technique to teach such concepts. In the pilot study, I intended not to focus on this misconception; however, it was there all the time, so I decided to include it in the dissertation to see how widespread it was among graduate students—and it was common.

When revealed, misconceptions could be a great introduction to a particular topic taught in classrooms. Not every educator will use this tool to strengthen learners’
conceptual understandings of a particular topic. Some educators tend to use revealed misconceptions to further confuse students or trick them on exams. Not all researchers would be motivated to help students master concepts but rather help educators develop exams. For example, in the study by Lamichhane et al. (2018), a suggestion was made at the end of their research paper about using misconceptions as plausible distractors for multiple choice questions used by instructors. The aim of this current research, however, was to help educators use misconceptions revealed by this dissertation as an introduction to help students avoid alternative misconceptions. Once educators spend a good amount of time talking about these misconceptions, these areas could be used to develop exams. I highly suggest spending some time helping students construct scientific, acceptable mental representations rather than using these findings to trick or trap most of the students in diagnosing misconceptions rather than testing students’ knowledge.

This dissertation raised other questions. How many details should non-chemistry major students know about chemistry to classify their learning to be effective, deep learning? Does the presence of these misconceptions affect their medical practices if they work in medicine? To answer these questions, I would interview experts such as pharmacists and pharmaceutical researchers to know their opinions about the risks of having these misconceptions in the medical fields.

Concluding Paragraph

In this chapter, a summary of the results was reported. Its results were compared and contrasted with those from previous studies. Some limitations were discussed for future work. The implications from this study were discussed along with the findings being linked to theories presented in Chapter II of this dissertation.
REFERENCES


Bak, L. K., & Schousboe, A. (2017). Misconceptions regarding basic thermodynamics and enzyme kinetics have led to erroneous conclusions regarding the metabolic importance of lactate dehydrogenase isoenzyme expression: LDH isoenzyme distribution and lactate metabolism. Journal of Neuroscience Research, 95(11), 2098-2102. doi:10.1002/jnr.23994


doi:10.1103/PhysRevSTPER.4.020104


doi:10.1037/0022-0663.82.1.135


APPENDIX A

OVERVIEW OF MAJOR METABOLIC PATHWAYS
Overview of Major Metabolic Pathways

Proteins → Glucose → Pyruvate → TCA

NH₃ → Pyruvate

Fatty acids & Glycerol → Pyruvate

Aerobic

Anaerobic
APPENDIX B

CONSENT FORM FOR HUMAN PARTICIPANTS
IN RESEARCH
CONSENT FORM FOR HUMAN PARTICIPANTS IN RESEARCH

The University of Northern Colorado

Project title: Assessment of Conceptual Understanding of Metabolic Pathways
Researcher: Amani M. Abdugadar, Doctoral student in Chemical Education, University of Northern Colorado
Phone number: (970) 405-4991        E-mail: Amani.Abdugadar@unco.edu
Research advisor: Jerry P. Suits, Associate Professor, Department of Chemistry and Biochemistry, University of Northern Colorado
Phone number: (970) 351-1169          E-mail: Jerry.Suits@unco.edu

The primary goal of this research project is to identify and assess some of students’ conceptions of metabolic pathways. The accessible population of this study is students who are taking biochemistry courses CHEM 581, 481, SES 322, and 622. In addition, we selected these students because they frequently hold some misconceptions that they bring to class (pre-conceptions) or develop during instruction. Having such misconceptions can prevent them from constructing new conceptual knowledge of the metabolic pathways.

The first part of this research project is designed to examine students’ conceptual understanding of metabolic pathways using interview questions. The researcher wrote these questions using simpler, less technical language, which can be understood by all participants; furthermore, the questions are balanced between not being so hard as to be frustrating nor so easy as to be boring. In the interview, I will discuss with the student her/his own answers of an open-ended test (a pre-test) that consists of eight items each represent an essential concept in understanding metabolism. After the interview, the student will be assigned to one of a three treatment groups. After that, a post-test will be given to the student, and the whole study will take no longer than 40 minutes including the post-test. I will contact the students who are willing to participate in this study, and we will meet on-campus for 2 separate times (before and after the treatment).

There are no anticipated risks to participants. You may feel a little anxious when taking the test; however, the results of the test will not affect your grade, and your instructor will never see the results. The questions on the pre- and post-tests are based on the course you already are taking, and the topics will be covered by instruction in the course. Your participation is confidential. The data will be coded and stored separately from your personal identification in a locked filing cabinet to which only my research advisor and I have access. In addition, confidentiality will be maintained during the data collection, analysis, and reporting of results by storing the data in a locked file cabinet by the researcher. The data will be coded and stored separately from participants’ personal information. The results will be reported in aggregate or group form so that individual students’ responses cannot be identified. For students who finish the post-test, the compensation will be 20 dining dollars that can be used at campus retail locations.
Participation is voluntary. You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. A copy of this form will be given to you to retain for future reference. If you have any concerns about your selection or treatment as a research participant, please contact Sherry May, IRB Administrator, Office of Sponsored Programs, 25 Kepner Hall, University of Northern Colorado Greeley, CO 80639; 970-351-1910.
Print name:__________________________
Participant’s Signature:_________________________________________
Date:_____________
Researcher’s Signature:_________________________________________
APPENDIX C

DEMOGRAPHIC QUESTIONNAIRE
Demographic Questionnaire

1. What is your gender? _____ Male/ Female

2. What is your race? _____________________________________________

3. What year of college are you in? _________________________________

4. What is your academic major? ________________________________

5. What is your approximate GPA? _________

6. What is your attitude towards Chemistry? ____________

7. List any college biology or biochemistry courses that have you taken including the instructor name and the year the course was taken (if possible).

   Course name   Semester/Year
APPENDIX D

OPEN RESPONSE TEST FOR THE PILOT STUDY
1. Complete the overview diagram attached.

2. The reaction below, Reaction A, occurs in living cells:

\[ \text{C}_6\text{H}_{12}\text{O}_6 \text{(aq)} + 6 \text{O}_2 \text{(g)} \rightarrow 6 \text{CO}_2 \text{(g)} + 6 \text{H}_2\text{O} \text{(l)} \]  

**Reaction A**

A. Do you classify this reaction as an oxidation-reduction reaction? 
__________________________

B. Please explain how you got your answer.

3. In Reaction A above:

A. Is it an endothermic or exothermic process? _______________________

B. Please explain how you got your answer.

4. Which molecules are more stable... the reactants or products? _____________

5. The reaction below, Reaction B, occurs when glucose is burned in a test tube.

\[ \text{C}_6\text{H}_{12}\text{O}_6 \text{(s)} + 6 \text{O}_2 \text{(g)} \rightarrow 6 \text{CO}_2 \text{(g)} + 6 \text{H}_2\text{O} \text{(l)} \]  

**Reaction B**

A. What are some differences between Reactions A and B?
__________________________

__________________________

B. What are the similarities between these two reactions?

C. Would you expect the change in free energy of reactions A and B to be the same?
6. Draw the energy diagram for the reaction shown below.

ATP + glucose $\leftrightarrow$ ADP + glucose-6-P

7. A. Which glycolytic enzymes are potential control points?

   B. Explain your answer.
8. A. In the reaction below, one H atom from the malate molecule is captured by the NAD\(^+\) molecule. Circle this H atom.

\[
\begin{align*}
\text{Malate} & \quad + \quad \text{NAD}^+ \\
\text{Oxaloacetate} & \\
\end{align*}
\]

B. Knowing that the \(\Delta G^\circ\) value for this reaction is +29.7 kJ/mol, do you expect malate or oxaloacetate to have the higher concentration at equilibrium? Circle one molecule.

C. What effect would pH have on this reaction?

D. Please explain how you got your answer in both A and B.
APPENDIX E

THE OBJECT-SPATIAL IMAGERY AND VERBAL QUESTIONNAIRE
<table>
<thead>
<tr>
<th></th>
<th>Architecture interests me more than painting.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.</td>
<td>Essay writing is difficult for me and I do not enjoy doing it at all.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>3.</td>
<td>I am a good Tetris player.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>4.</td>
<td>I am always aware of sentence structure.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>5.</td>
<td>I am better at manipulating equations and numbers than pictures and diagrams.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>6.</td>
<td>I am good at visualizing the direction that a pool ball might travel in.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>7.</td>
<td>I can close my eyes and easily picture a scene that I have experienced.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>8.</td>
<td>I can easily imagine and mentally rotate three-dimensional geometric figures.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>9.</td>
<td>I can easily remember a great deal of visual details that someone else might never notice. For example, I would just automatically take some things in, like what color is a shirt someone wears or what color are his/her shoes...</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>10.</td>
<td>I can easily sketch a blueprint for a building that I am familiar with.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>11.</td>
<td>I enjoy being able to rephrase my thoughts in many ways for variety’s sake in both writing and speaking.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>12.</td>
<td>I find it difficult to imagine how a three-dimensional geometric figure would exactly look like when rotated.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>13.</td>
<td>I have a photographic memory.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>14.</td>
<td>I have better than average fluency in using words.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>15.</td>
<td>I have difficulty expressing myself in writing.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>16.</td>
<td>I have excellent abilities in technical graphics.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>17.</td>
<td>I memorize material mostly by the use of verbal repetition.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>18.</td>
<td>I normally do not experience many spontaneous vivid images; I use my mental imagery mostly when attempting to solve some problems like the ones in mathematics.</td>
<td>1</td>
<td>2</td>
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</tr>
<tr>
<td>19.</td>
<td>I prefer schematic diagrams and sketches when reading a textbook instead of colorful and pictorial illustrations.</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>20.</td>
<td>I remember everything visually. I can recount what people wore to a dinner and I can talk about the way they sat and the way they looked probably in more detail than I could discuss what they said.</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>21.</td>
<td>I tell jokes and stories better than most people.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>22.</td>
<td>I usually do not try to visualize or sketch diagrams when reading a textbook.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>23.</td>
<td>I was very good in 3-D geometry as a student.</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>24.</td>
<td>If I were asked to choose among engineering professions, language arts or visual arts, I would choose language arts.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>25.</td>
<td>If I were asked to choose between engineering professions and visual arts, I would prefer engineering.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26.</td>
<td>If I were asked to choose between studying architecture and visual arts, I would choose visual arts.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>27.</td>
<td>In high school, I had less difficulty with geometry than with art.</td>
<td></td>
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<tr>
<td>28.</td>
<td>My graphic abilities would make a career in architecture relatively easy for me.</td>
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</tr>
<tr>
<td>29.</td>
<td>My images are more like schematic representations of things and events rather than like detailed pictures.</td>
<td></td>
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</tr>
<tr>
<td>30.</td>
<td>My images are more schematic than colorful and pictorial.</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>31.</td>
<td>My images are very colorful and bright.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32.</td>
<td>My images are very vivid and photographic.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33.</td>
<td>My mental images of different objects very much resemble the size, shape and color of actual objects that I have seen.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>34.</td>
<td>My mental pictures are very detailed precise representations of the real things.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35.</td>
<td>My verbal skills are excellent.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>36.</td>
<td>My visual images are in my head all the time. They are just right there.</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>37.</td>
<td>Putting together furniture kits (e.g., a TV stand or a chair) is much easier for me when I have detailed verbal instructions than when I only have a diagram or picture.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>38.</td>
<td>Sometimes my images are so vivid and persistent that it is difficult to ignore them.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>39.</td>
<td>When entering a familiar store to get a specific item, I can easily picture the exact location of the target item, the shelf it stands on, how it is arranged and the surrounding articles.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>40.</td>
<td>When explaining something, I would rather give verbal explanations than make drawings or sketches.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>41.</td>
<td>When I hear a radio announcer or a DJ I’ve never actually seen, I usually find myself picturing what he or she might look like.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>42.</td>
<td>When I listen to people describe their experiences, my vivid imagery always supports their stories; I try to imagine that I was there.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>43.</td>
<td>When reading a textbook where things are clearly described in words, I find illustrations distracting because they interfere with my ability to focus on the material.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>44.</td>
<td>When reading fiction, I usually form a clear and detailed mental picture of a scene or room that has been described.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>45.</td>
<td>When remembering a scene, I use verbal descriptions rather than mental pictures.</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
</tbody>
</table>
APPENDIX F

OPEN-RESPONSE TEST FOR THE DISSERTATION
Open-Response Test for the Dissertation

A. Which of the following is true regarding glycolysis?

   i. There is a net oxidation of substrate carbon atoms.
   ii. There is no net release of free energy.

B. Explain your answer.

A. The reaction catalyzed by the enzyme aldolase has a $\Delta G^\circ \approx +23$ kJ/mol. This reaction is shown in the glycolysis pathway (reaction 4) see question 4. In muscle cells, the reaction proceeds in this same, forward direction. How can this occur?

   i. This $\Delta G^\circ$ means it is thermodynamically favored.
   ii. The enzyme changes the $\Delta G$ of the reaction in cells to something favorable.
   iii. The concentration of reactant(s) must be significantly greater than product(s) in cells.
   iv. The concentration of product(s) must be significantly greater than reactant(s) in cells.
   v. None of the above.

B. Explain your answer.
Draw the energy diagram for the reactions shown below.

A. \( \text{ADP} + \text{PO}_3^{2-} \rightleftharpoons \text{ATP} \)

B. \( \text{phosphoenolpyruvate} \rightleftharpoons \text{pyruvate} + \text{PO}_3^{2-} \)

C. \( \text{ADP} + \text{phosphoenolpyruvate} \rightleftharpoons \text{ATP} + \text{pyruvate} \)
A. Which glycolytic enzymes serve as potential control points? Circle these reactions.

B. Explain your answer.
5. In the reaction below, one H atom from the malate molecule is captured by the NAD$^+$ molecule

\[
\text{Malate} + \text{NAD}^+ \rightleftharpoons \text{Oxaloacetate} + \text{NADH} + \text{H}^+
\]

A. Circle this H atom.

B. Knowing that the $\Delta G^\circ$ value for this reaction is $+29.7 \text{ kJ/mol}$, do you expect malate or oxaloacetate to have the higher concentration at equilibrium? Circle one molecule.

C. What effect would pH have on this reaction?

D. Please explain how you got your answer in both A and B.
APPENDIX G

SEMI-STRUCTURED QUESTIONS FOR THE FINAL INTERVIEW
Semi-Structured Questions for The Final Interview

1. How do you describe your experience with the animation you have seen?

2. Do you recommend the use of this animation in future courses? Why or why not?

3. Are the topics covered by the animation relevant to the information in your lecture or textbook? If they are different, how is that?

4. Do you have any recommendations or a critique on the animation you have seen?

5. If you have a particular conception/misconception mentioned to you by the researcher. Why do you think you developed such a conceptual understanding?

6. Do you like to add any thought?
APPENDIX H

INSTITUTIONAL REVIEW BOARD APPROVAL
Institutional Review Board

DATE: June 9, 2017

TO: Amani Abdugadar, M.S
FROM: University of Northern Colorado (UNCO) IRB

PROJECT TITLE: [923023-2] Assessment of Conceptual Understanding of Metabolic Pathways
SUBMISSION TYPE: Amendment/Modification

ACTION: APPROVAL/VERIFICATION OF EXEMPT STATUS
DECISION DATE: June 8, 2017
EXPIRATION DATE: June 8, 2021

Thank you for your submission of Amendment/Modification materials for this project. The University of Northern Colorado (UNCO) IRB approves this project and verifies its status as EXEMPT according to federal IRB regulations.

Hello Amani,

Thank you for your modifications. Your IRB application is approved.

Sincerely,

Nancy White, PhD, IRB Co-Chair

We will retain a copy of this correspondence within our records for a duration of 4 years.

If you have any questions, please contact Sherry May at 970-351-1910 or Sherry.May@unco.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB’s records.
DATE: February 6, 2019

TO: Amani Abdugadar, M.S

FROM: University of Northern Colorado (UNCO) IRB

PROJECT TITLE: [923023-5] Assessment of Conceptual Understanding of Metabolic Pathways

SUBMISSION TYPE: Amendment/Modification

ACTION: APPROVAL/VERIFICATION OF EXEMPT STATUS

DECISION DATE: February 4, 2019

EXPIRATION DATE: June 8, 2021

Thank you for your submission of Amendment/Modification materials for this project. The University of Northern Colorado (UNCO) IRB approves this project and verifies its status as EXEMPT according to federal IRB regulations.

We will retain a copy of this correspondence within our records for a duration of 4 years.

If you have any questions, please contact Nicole Morse at 970-351-1910 or nicole.morse@unco.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB’s records.
APPENDIX I

SCREENSHOTS FROM THE MULTIMEDIA VIDEO DEVELOPED BY AMANI ABDUGADAR
Screenshots from the Multimedia Video
Developed by Amani Abdugadar

Energy Diagram for Exergonic Reactions (Exothermic)

Chemical Potential Energy

Reaction Progress

Energy Diagram for Exergonic Reactions (Exothermic)

Chemical Potential Energy

Reaction Progress
Energy Diagram for Endergonic Reactions (Endothermic)

Chemical Potential Energy

Reaction Progress

Energy Diagram for Endergonic Reactions (Endothermic)

Chemical Potential Energy

Glucose $\Delta G^\circ$ Energy absorbed

Reaction Progress
How important are endergonic processes?

Can you think of their function and purpose?
The energy diagram for reaction (1) in glycolysis.
In most cases, the energy required to drive endergonic reactions comes from ATP hydrolysis, by which cells break down ATP to use its energy.

Does breaking the bond in ATP generate energy? Explain your answer using the energy profile (reaction coordinate diagram).

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**Reversible Reactions**

A + B  \[\rightleftharpoons\]  C + D

\[\Delta G = \Delta G^\circ + RT \ln \left(\frac{[C][D]}{[A][B]}\right)\]

At equilibrium:

\[\Delta G^\circ = -RT \ln \left(\frac{[C][D]}{[A][B]}\right)\]
### Table of Physiological Free Energy Changes for Glycolytic Pathways

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Enzyme</th>
<th>$\Delta G_0^\circ$ (kJ · mol$^{-1}$)</th>
<th>$\Delta G$ (kJ · mol$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hexokinase</td>
<td>$-20.9$</td>
<td>$-27.2$</td>
</tr>
<tr>
<td>2</td>
<td>PGI</td>
<td>$+2.2$</td>
<td>$-1.4$</td>
</tr>
<tr>
<td>3</td>
<td>PK</td>
<td>$-17.2$</td>
<td>$-28.9$</td>
</tr>
<tr>
<td>4</td>
<td>Aldolase</td>
<td>$+22.8$</td>
<td>$-5.9$</td>
</tr>
<tr>
<td>5</td>
<td>TIM</td>
<td>$+7.0$</td>
<td>$-0$</td>
</tr>
<tr>
<td>6 + 7</td>
<td>GAPDH + PGK</td>
<td>$-16.7$</td>
<td>$-1.1$</td>
</tr>
<tr>
<td>8</td>
<td>PGM</td>
<td>$+4.7$</td>
<td>$-0.6$</td>
</tr>
<tr>
<td>9</td>
<td>Enolase</td>
<td>$-3.2$</td>
<td>$-2.4$</td>
</tr>
<tr>
<td>10</td>
<td>PK</td>
<td>$-23.0$</td>
<td>$-13.9$</td>
</tr>
</tbody>
</table>
APPENDIX J

A TRANSCRIPTION FOR THE VIDEO
NARRATED BY ANNA PIERCE
In living systems, energy is needed to drive various functions, which is obtained through exergonic reactions. An exergonic reaction refers to a reaction where energy is released. Gibbs free energy (ΔG) is negative for these reactions, and they usually do not require energy to proceed, and therefore occur spontaneously. An example of exergonic reaction is the hydrolysis of the high-energy compound adenosine triphosphate (ATP) which releases 30.5 kJ/mol of energy.

On the other hand, an endergonic reaction refers to a chemical reaction in which energy is being used in the overall reaction, making the reaction non-spontaneous and thermodynamically unfavorable. Energy is being absorbed as the reaction proceeds. Due to this consumption of energy, standard change in Gibbs free energy (ΔG) is a positive value. The first step in the metabolism of glucose, which is its conversion to glucose-6-phosphate, is an example of endergonic reactions. Yet the direct reaction of glucose and the inorganic phosphate group is thermodynamically unfavorable (ΔGo= +13.8 kJ/mol).

Coupled reactions:

Catabolic reactions carry out the exergonic oxidation of nutrient molecules. The free energy thereby released is used to derive such endergonic process as anabolic reactions. The exergonic reactions of “high-energy” compounds can be coupled to endergonic processes to drive them to completion. To illustrate this concept, let us consider the last two examples of phosphoryl group-transfer reactions. In cells, the endergonic conversion of glucose to glucose-6-phosphate is coupled to the exergonic
cleavage of ATP so the overall reaction is thermodynamically favorable releasing 16.7 kJ/mol.

The free energy change $\Delta G$ of a reversible reaction is related to the standard free energy change $\Delta G_0$ and the concentration of the reactants and products.

$$\Delta G = \Delta G_0 + RT \ln \left( \frac{[C][D]}{[A][B]} \right)$$

at equilibrium when $\Delta G=0$, this equation becomes,

$$\Delta G_0 = -RT \ln K_{eq}$$

When the reactants are present at values close to their equilibrium values, metabolic reactions are said to be near-equilibrium reactions. This table shows you the free energy changes for glycolytic pathway, and the highlighted reactions show represent the reversible reactions. Because $\Delta G$ values are close to zero, they can be relatively easily reversed by changing the ratio of products to reactants. When the reactants are in excess of their equilibrium concentrations, the net reaction proceeds in the forward direction until the excess reactants have been converted to products and equilibrium is attained. That is not the case for the other reactions that function far from equilibrium; that is, they are irreversible. Changes in substrate concentrations therefore have a relatively little effect on the rate of an irreversible reaction. Thus, to control those reactions, only changing the activity of the enzymes that catalyzes these reactions can alter the rate. That what makes the glycolytic reactions 1, 3 and 10, the major regulatory points (Voet et al., 2013).