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Examining some of the Challenges that Students Face in Learning about Metabolic Pathways in a Traditional Biochemistry Course

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Metabolic pathways are one of the most challenging topics in biochemistry to conceptualize because it requires that students combine many ideas from different disciplines. Some students consider rote learning and memorization of metabolic pathways equivalent to understanding of these concepts and can contribute to a meaningful learning of the phenomenon. This research study aims to examine some of the students' difficulties in learning about metabolic pathways, their approaches to learning about the concepts, and the role that memorization has on their performance in the course. The research took place at an urban, commuter, and minority serving public college. The research methodology was the analysis of an instrument used in this research study which was a survey comprised of Likert-scale and open-ended questions. The number of research participants is 37 students who are enrolled in biochemistry or have completed at least one biochemistry course. The survey was optional and participant's identity remained anonymous. Our research findings suggest that students face difficulties in learning about metabolic pathways due to their reliance on memorization of reactions, enzymes, and steps, which is a superficial approach to learning and does not lead to development of conceptual understanding. Another noteworthy finding is that students struggle with providing an explanation of what is happening at the molecular level during the metabolic pathways reactions.

Keywords: metabolic pathways, education research, rote learning, students, learning

INTRODUCTION

The study of biochemistry is broadly defined as the application of chemistry to the study of the biological processes at the cellular and molecular levels. Metabolism is more than

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just a long list of chemical reactions arranged into complex sequences. The biological and chemical details of metabolism help us grasp how the human body works. It is vital that students understand the concept of metabolism because it impacts all cellular functions and helps maintain homeostasis for an individual (Sherwood, 2015). Choosing to ignore the conceptual aspect of metabolism results in disregarding how the enzymes drive the reaction forward, the different ways cells regulate the metabolic pathways, and the significance of essential molecules (Metallo & Vander Heiden, 2013). The amount of information biochemistry classes cover is substantial, specifically metabolic pathways which combine many different topics from molecular biology and chemistry.

There are many reasons why students often struggle to effectively learn about the metabolic pathways that is taught in first-year biochemistry courses. New biochemistry students can be intimidated by the complex list of chemical formulae that make up biochemical pathways and feel that the subject is incomprehensible (Fardilha et al., 2010). The numerous metabolites and enzymes that make up metabolic charts often have no meaning to students at first because they lack a thorough understanding of molecular biology and chemistry that is required to grasp the principles behind metabolic pathways. Ineffective teaching techniques that encourage memorization and too much coursework can also discourage students from adequately learning about biochemistry (Garcia et al., 2018). Most students have other priorities and aim to get a decent grade in their biochemistry course, which motivates them only to review what they need to know to pass the exam. The complex nature of metabolic pathways, inadequate teaching techniques, the lack of a solid foundation, and arduous coursework, prevent students from effectively learning about this subject (Dweck et al., 2014).

Biochemistry undergraduate courses often task students with remembering the names and chemical structures of the molecules involved in metabolic pathways. It is not uncommon for students to memorize the order of metabolites and enzymes in metabolic pathways a few days before their test (Rabinowitz & Vastag, 2012). Essentially, students cannot learn about metabolic pathways without connecting their previous understanding of the topic to the details teachers present in their classrooms (Novak, 1998). Rote memorization is constantly repeating new information to memorize it. Indifferent biochemistry students will usually forget the terminology associated with a particular metabolic pathway because they utilize rote memorization to learn the names of metabolites and enzymes without having any knowledge of their structure, function, and overall purpose (Bretz, 2001).

Learning Biochemistry involves understanding a combination of many details at once, which Johnstone termed “multilevel thought.” In order to comprehend metabolic pathways, students need to simultaneously incorporate three levels (macroscopic, submicroscopic, and symbolic) of learning (Johnstone, 1991). Students learning about metabolic pathways use multilevel thought to think about molecules (sub-microscopic) and organism (macroscopic) are affected by the sequence of chemical reactions (sub-microscopic) (Johnstone, 1991). It is critical that students develop knowledge in all three levels to adequately understand metabolic pathways; however, this takes time because introducing all three levels together is not efficient and can easily lead to cognitive overload (Johnstone, 2000). If a student is struggling with one level, it may cause problems with the others.

Chemistry courses, including biochemistry, incorporate abstract ideas that require students to visualize what is happening at the sub-microscopic and macroscopic levels. An inexperienced biochemistry student may struggle to connect all the levels to understand the significance of metabolism. Generally, in chemistry courses, the symbolic level is the least difficult, and students can solve problems without thinking about the events at the sub-microscopic level because it is easy to plug in numbers and symbols (Treagust et al., 2003). The same idea can be applied to biochemistry students studying metabolism because people can ignore the conceptual details of the sub-microscopic and macroscopic levels to answer exam questions that involve using symbols, in particular, the name of components in metabolic pathways. An example is that students do not have to think about is why the citric acid cycle is essential for cellular function and overall health. They can also effortlessly write out the words "Citrate" or "NADH" without knowing the nature and function of these molecules.

The first step in glycolysis is the enzyme hexokinase converting glucose to glucose-6 phosphate. Without any visual models to understand structure and function, the student will not be able to see that hexokinase facilitates the transfer of phosphate group from ATP to the hydroxyl group on the sixth carbon of glucose. They also cannot visualize how the enzyme interacts with the sugar. If students ignore the structure and molecular organization of glucose 6-phosphate, then they will not see that the purpose of this step was to give the sugar an overall net negative charge to prevent it from leaving the cell (Li et al., 2015). Visualization skills allow students to relate how the structure and function of metabolites play a role in metabolic pathways (Schönborn & Anderson, 2006).

An example that delineates the importance of visualization skills is the common misinterpretations students associate with the citric acid cycle. The citric acid cycle is often illustrated as a circular pathway in biochemistry textbooks because the pathway starts and ends with the same compound, oxaloacetate. The pathway utilizes enzymes to decarboxylate carbon compounds because the overall purpose of the citric acid cycle is to extract high energy electrons from these molecules to reduce NAD+ and FADH. Forming NADH and FADH2 is essential because they play a vital role in oxidative phosphorylation. One cycle produces two carbon dioxide molecules, one ATP, one GTP, three NADH, and one FADH2 (Berg et al., 2007).

After reviewing the concepts of the subject, educators need to explain the symbolism associated with the external representations because it may not be evident to students and could potentially confuse learners (Ametller & Pinto, 2002). Biochemistry instructors also need to stress the limitations of these models and specify what they represent to prevent students from developing alternative conceptions about the subject. An example specific to metabolic pathways is that most metabolic charts do not emphasize the molecular phenomena occurring in the cell when the metabolites are transitioning. A student visualizing how the molecules interact with each other while examining a metabolic chart may conceptualize inaccurate details, which is why it is recommended for teachers to explain what the chart can and cannot illustrate (Metallo & Vander Heiden, 2013; Roth, 2002).

Biochemistry courses are usually lecture driven, involve arduous coursework, and full of dense information that easily overwhelms students (Copper & Stowe, 2018). Exams in a typical biochemistry course follow a multiple-choice format and require students to memorize information. This teaching method results in students not understanding the principles of metabolic pathways because educators are not discouraging rote memorization and utilizing active learning techniques (Watters & Watters, 2007). Students face numerous difficulties in learning about chemistry concepts due to their reliance on algorithmic problem solving, calculator use, and plugging numbers into equations instead of depending on the development of conceptual understanding to solve problems (Salame et al., 2022).

Strict lecture courses gradually present the information to students but fail to teach them the vital thinking skills that they need to excel academically (Wilson & Conyers, 2016). Most students fail to grasp the concepts of metabolic pathways because, without thinking skills such as visual literacy and efficient use of the working space, many students rely on memorizing answers for their exams. Many students perform poorly in their biochemistry courses because they only review the basics and rely on rote memorization of metabolic pathways instead of studying in a way that leads to an efficient understanding of the material. Preparing for exams like this impedes the learning process and results in inadequate course performance (Kulak & Newton, 2014; Linenberger & Holme, 2014; Bretz, 2001). To combat this, educators need to focus on keeping their students engaged and taking a more active role during classroom lectures (Mayer, 2003).

Teaching an overwhelming amount of content is counterproductive because it results in a decrease in conceptual understanding (Vidic & Weitlauf, 2002). Many students lack the time and motivation to learn about a large amount of information, so they resort to temporarily memorizing everything for their exams (Dweck et al., 2014). Biochemistry students can earn good grades without understanding the principles of metabolism because it is easy to quickly remember the words “Glucose”, “Pyruvate”, “Acetyl-Coa”, and “lactate” without knowing what they mean. Classes with excessive course-work encourage students to retain facts and procedures instead of working to understand the concepts and underlying ideas (Reingold, 2001).

Many instructors deal with this by not expecting students to know the structures of all the amino acids, nucleotides, and metabolites taught in biochemistry, but still expect them to understand their significance (White, 2005). To improve academically in biochemistry, students must work on their conceptualizing skills and construct a strong framework of the supporting subjects. Someone that is able to comprehend metabolic pathways efficiently will most likely be proficient in molecular biology and chemistry. If students reinforce their knowledge on similar disciplines, it will translate over to biochemistry by helping them improve their incorporation of new material (Moore, 1987; Watters & Watters, 2007). The majority of the students in the lecture found that categorizing concepts instead of sequentially listening to the information in lectures helped them think more deeply about the subject and bring together multiple ideas to visualize the process (Rowland et al., 2011).

Guiding Research Questions

1. What are some of the students' difficulties in learning about metabolic pathways?

2. What approaches do students use in solving metabolic pathways related problems?

3. Do students rely on the role of rote learning and memorization instead of conceptual understanding in solving metabolic pathways problems?

METHOD

The goal of this research investigation is to examine challenges that students face in learning about metabolic pathways in a traditional biochemistry course. The investigation took place at the City College of New York during the Spring Semester of 2020. The City College of New York is a minority serving public institute. The participants have completed or were enrolled in a Biochemistry course. Our research instrument comprised a survey that consisted of Likert-type and open-ended questions. The survey was examined by two separate faculty members in science education who agreed that the questions adequately capture the investigation about challenges in metabolic pathways. The reliability coefficient was assessed to be 0.80 through the use of test-retest reliability method. The survey was administered and collected from 37 participants in accordance to the Internal Review Board (IRB).

The Likert-type questions were on a five-point scale that were converted into numerical values as follow: Strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5). We performed a single factor ANOVA on our Likert-type questions found $P < .001$. P-value < 0.05, which is strong evidence against the null hypothesis and shows that there is stronger relationship between the variables. Furthermore, the mean square for our data is 5.71 which is much larger than the mean square within the treatments which is 1.05.

The data collected were tabulated and the average answer from respondents was calculated for each question and placed in a table. For one of one of the open ended questions, the answers were evaluated on a scale from 1 to 5 based on a rubric that was developed that works well for this type of research. The rubric was finalized after four re-readings of the written surveys. Answers with a score of 5 show complete agreement with role of memorization on learning of metabolic pathways. Whereas a score of 1 represents a complete disagreement with the role and importance of memorization on the learning and understanding of metabolic pathways. Two of the researchers independently applied the rubric shown to the entire set of data. The three sets of results agreed over 90% of the time. The responses where the rubric score varied were not different by more than one unit. The two researchers met and discussed the responses that were not unanimous using the rubric until an agreement was reached. The rubric reflects the representative responses that were observed. We then converted the answers into numerical values, took the average and placed the question and average values in a table.

For the other questions we collected the data, compiled the answers based on categories and similarities, converted it into percentages, and used it in bar and pie charts based on the percentages of the answers provided by the research participants. We should note that all of the research data was based on the survey that was administered and collected from research participants. The percentages were calculated based on the number of participants who provided answers that fit into similar categories based on the total number of responses.

FINDINGS AND DISCUSSION

The data presented in Table 1 is based on the Likert-scale questions by taking the mean from all of the respondents. Additionally, one of the open ended questions is also presented in Table 1. The respondent answers were coded based on a rubric and the mean was calculated.

Table 1
Likert-type and open ended questions and average answer from respondents

Likert-type Question	Average Answer from Respondents
Learning about metabolic pathways is one of the most difficult parts of biochemistry.	3.61
I relied on memorization to pass examinations about metabolic pathways.	3.47
I understood the molecular phenomena that were occurring in the metabolic pathways we were learning about.	3.45
I struggled to remember all the names of the intermediates and enzymes.	3.56
I learned enough from metabolic charts and diagrams to explain the phenomena behind metabolic processes such as the citric acid cycle, glycolysis, gluconeogenesis, and oxidative phosphorylation.	4.28
Knowledge from my previous science courses was vital in understanding metabolism.	4.28
Open-ended Question	Average Answer from Respondents
The following picture is a metabolic chart of glycolysis. Do you feel that analyzing this pathway and memorizing the name of the intermediates is enough information to understand the topic and perform adequately on biochemistry exams? Why or why not?	2.06

The data presented in Table 1 present evidence that students agree that learning metabolic pathways is the most difficult part of a biochemistry course, they depended on memorization to pass the metabolic pathways related examination questions, and struggled to the recall the myriad names of intermediates and enzymes. Memorizing the name and molecular structure of multiple metabolites and enzymes, and understanding the physiological significance behind metabolic pathways is a strenuous task for the average student because they have to do it in a short period of time (Silva & Batista, 2003).

Students also have the perceptions that they understood the molecular phenomenon taking place during metabolic pathways and learned enough from metabolic charts and diagrams to explain the phenomena behind metabolic processes. Furthermore, that data shows that students agree that knowledge learnt in previous science courses is vital in understanding metabolism. It is noteworthy that students disagree with the role of memorization in developing understanding and in performance in biochemistry.

The following is Figure 1, which is a pie chart representing the respondents' views on the difficult parts of learning about metabolic pathways.

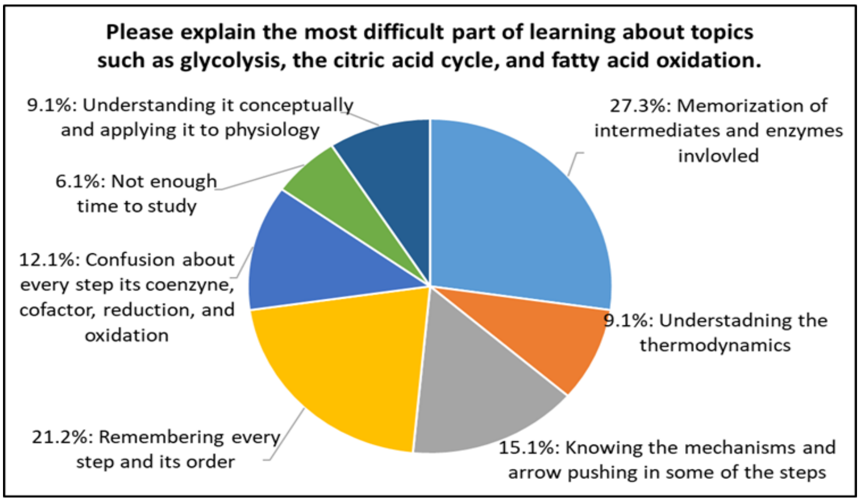

Figure 1
Pie chart representing the difficult part about learning metabolic pathways

A sizeable percentage (27.3%) of students felt that the most difficult part in learning about metabolic pathways was memorization of both intermediates and enzymes involved in the process (Figure 1). This was followed by 21.2% of student who revealed that remembering every step and its order as the most challenging aspect of learning about metabolic pathways. These results are consistent with research findings in the field that suggest students' view biochemistry courses as collection of unrelated facts and conception, which justifies the use rote learning and memorization to achieve passing grades in the course (Minasian-Batmanian et al., 2006).

Figure 1 also shows that 9.1% of students view understanding of the thermodynamics as one of the most difficult part of learning about metabolic pathways. One research study identified three sources of challenges associated with students learning. They include: "the influence of enzyme inhibition on metabolic pathways; understanding of the second law of thermodynamics; and the bioenergetics of these pathways" (Anderson & Grayson, 1994). Another 9.1% of research participants suggest that understanding metabolic pathways conceptually and applying them physiologically as the most challenging part of learning about these concepts. Researcher report that one of the reasons for studying metabolic pathways is to understand the physiological importance of the process and why each part is essential to obtain the final molecule, not to memorize the different steps and names of compounds (Rabinowitz & Vastag, 2012).

In addition, 12.1% of students report that confusion about every step and its coenzyme, cofactor, oxidation, and reduction as the most difficult part in the learning about metabolic pathways. Biochemistry is a challenging course for both students and instructors due to its vast amount of knowledge covered, and its interdisciplinary nature due to the overlap between Biology, Chemistry, and Physics (Tibell & Rundgren, 2010). Furthermore, 15.1% of students reveal that knowing the mechanisms and the use of arrows in some of the steps as the most challenging part of learning about metabolic pathways and 6.1% of students claim that lack of time to study as hindrance to their learning of the concepts. Research in science education underscore the role of engaging students in mechanistic thinking which leads to improved problem solving competency in organic chemistry reactions and synthesis (Grove et al., 2012).

Figure 2 is a pie chart representing the respondents' perceptions of ways to improve their learning about metabolic pathways.

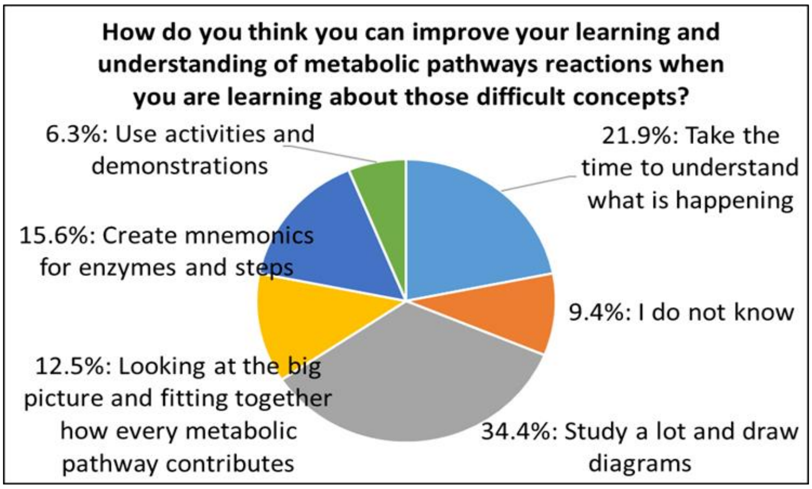

Figure 2
Pie chart of students input on improving learning and understanding of metabolic pathways

Figure 2 is a pie chart of the students' perception about improving learning and understanding of metabolic pathways. The students report (34.4%) that they rely on studying and drawing diagrams as approaches to improve their learning and understanding of the content. Another significant number of participants (21.9%) use taking the time to understand what is happening as their preferred method to learning and developing an understanding of metabolic pathways. To develop conceptual understanding of biochemical concepts, researchers in science education suggest that students need to integrate varied components that are multifaceted in nature (Orgill & Bodner, 2007).

We should note that 15.6% of research participants depend on creating mnemonics for enzymes and steps as they learn about metabolic pathways. This could be attributed to the instructors' assessment approach which would rely heavily on memorization and rote learning. Traditional biochemistry examinations usually use multiple choice format which assesses students' memorization of information which hinders students' development of understanding since instructors do not discourage rote learning (Minderhout & Loertscher, 2007).

Also, 12.5%, of students report that it is important to look at the big picture and understand how the different steps fit together to learn and understand metabolic pathways. This could include understanding what is happening at the molecular level in each step. The ability to visualize what is happening at the molecular level plays a significant role in the process of learning biochemistry. Visualization allows students to model complex and abstract content and to model the sub-microscopic level using abstract symbolic system (Kozma et al., 2000). Biochemistry courses are now prerequisite for the majority of health professionals who should have a well-developed understanding of metabolic pathways which is a major difficulty for students and causes them to lose their motivation and interest in the subject matter (Metzger, 2006). Lastly, 6.3% of participants recommend integrating demonstrations and activities into the instruction to improve learning and understanding of metabolic pathways.

Figure 3 is a bar chart representing students' explanations and understandings of metabolic pathways reactions. The data is shown as percentages of respondents with similar responses.

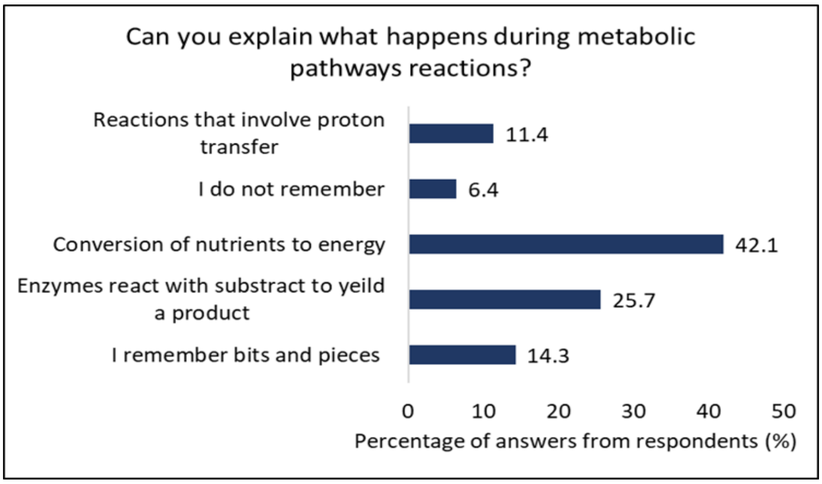

Figure 3
Bar chart depicting students' explanations of metabolic pathways reactions

Figure 3 presents the percentages of students' explanation on the steps, reactions, and processes that is taking place during metabolic pathways reactions. Research participants, 42.1%, reveal that metabolic pathways reactions involve conversion of nutrients to energy, whereas, 25.7% of students delineate that enzyme react with substrate to yield a product. When studying metabolic pathways, students need to focus on how the chemical nature of metabolites change during each transformation, the energy utilized for each step, the name of the different intermediates, and the molecular biology involved in the whole process (Schultz, 2005). Additionally, it was reported that students have alternative conceptions about metabolic pathways due to confusion about free energy and standard free energy, as well as, spontaneity of a biological reaction based on bond formations and bond dissociations (Wolfson et al., 2014). Furthermore, 14.3% of students report that they only remember bits and pieces about metabolic pathways reactions and 6.4% of students divulge that they do not remember what is happening during metabolic pathways reactions. In one study, researcher presented data that show students in biochemistry view the course as a separate collection of facts instead of an interconnected and interrelated concepts and themes and thus rely on surface learning and rote memorization approaches (Minasian-Batmanian et al., 2006).

The students (11.4%) reveal that metabolic pathways reactions involve proton transfer which is what is often shown in equations and formulae. Teaching of biochemical pathways focus on the presentation of symbolic level and neglect the development of students' visualization and understanding at the sub-microscopic level of the reactions. Sub-microscopic representational understanding is influential in development of conceptual understanding of biochemistry (Tsui & Treagust, 2003). Biochemistry learning requires students to relate, connect, and understanding the concept at the three levels of representations simultaneously (Bahar et al., 1999). The symbolic level is the equations and structures of molecules studies, the perceived part is the macroscopic level, and the level that cannot be seen or touched is the sub-microscopic representational level, which is most challenging for students. Students find it cognitively challenging, in the study of biochemistry, to understand the combination and relationship between the macroscopic, sub-microscopic, and symbolic levels of representations (Pavlinic et al., 2001).

The following is Figure 4, which is a bar chart representing the respondents' perceptions on what makes metabolic pathways reactions challenging to learn.

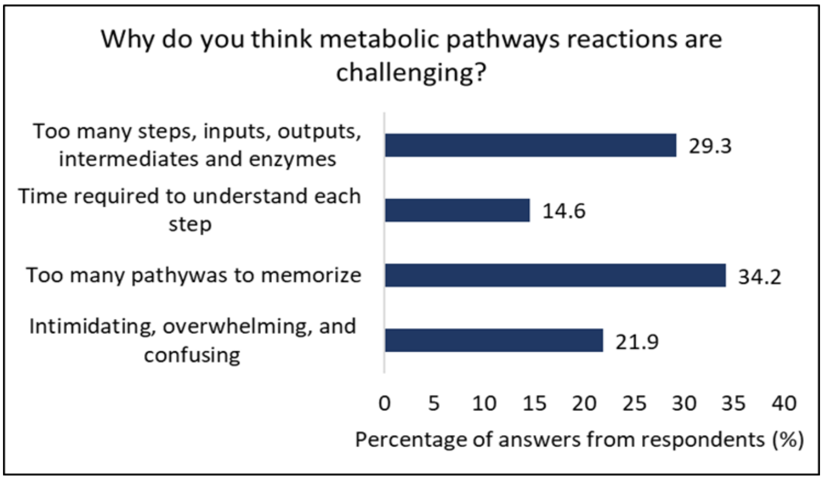

Figure 4
Bar chart depicting students' perceptions about what makes metabolic pathways reactions challenging

The data presented in Figure 4 depicts students' perceptions on the reasons that make metabolic pathways challenging. The data reveals that 29.3% of students find metabolic pathways challenging due to the numerous steps, reactions, intermediates, and enzymes. Additional 34.2% of students struggles with learning about metabolic pathways due to the large amount of material needed to be memorized. If the student chooses only to memorize the name of the molecules, then they will not comprehend the significance of the structure, function, and interactions of all the molecules (Kohn et al., 2018). Furthermore, overloading students with excessive information will reinforce studying techniques that involve rote memorization instead of building conceptual understanding, thinking skills, and problem-solving strategies (Reingold, 2001).

The figure also shows that 21.9% of students find biochemical pathways intimidating, overwhelming, and confusing. The immense course-work students need to deal within one semester of biochemistry usually overwhelms them, leading to poor academic performance and learning quality (Minderhout & Loertscher, 2007). It is noteworthy that 14.6% of students report that the time required to understand each and every step poses a challenge to their learning. This could be attributed to the fact that most biochemistry courses across the USA for the most part are lecture based and content heavy which leads to lack of conceptual understanding of chemical reactions and their important part in metabolic pathways (Fardilha et al., 2010). Another reason could be that biochemistry content is baffling to students and requires high levels of abstract thinking to learn (Silva & Batista, 2003). Learning biochemical pathways is an arduous process for the students due to its confusing multitudes of chemical formulae. Most students cannot comfortably imagine the molecular level and principles of metabolism, which is why educators must stress the importance of visualization skills (Seufert, 2003; Nerdel et al., 2003).

To improve the learning quality of biochemistry courses, teachers need to delineate the components of metabolic pathways because many chemistry students struggle to apply their knowledge to the real world (Bodner, 1991). Because people find the physical nature of chemistry challenging to learn about, instructors need to specify what the symbolic, such as, the names of intermediates and enzymes mean in metabolic charts to prevent students from blindly memorizing words and formulas that have no meaning to them (Johnstone, 1991; Bodner, 1991).

One effective active learning technique educators can utilize case-based learning, which incorporates real-world scenarios into classroom discussions. Discussing realistic scenarios while students are actively learning about metabolic pathways can help them solve problems by relating the information to concrete examples found in nature (Davies, 2004). Case-based learning is proven to improve student's skills in gathering relevant knowledge, and it enhances communication skills (Biggs & Tang, 2011). Teaching metabolic pathways while integrating varying teaching strategies based on constructivism and collaborative learning in biochemistry can be more effective in improving learning and enhancing students' performance when compared to traditional teaching approach (Sugano & Nabua, 2020).

CONCLUSION

The research investigation data suggest that students struggle learning about metabolic pathways, rely on memorization to perform on examinations related metabolic pathways, and struggle recalling the numerous names of intermediates and enzymes. The research shows that students have difficulties memorizing steps, enzymes, intermediates, and reactions involved in metabolic pathways and confusion about the myriad steps, coenzymes, cofactors, oxidation, and reduction. Memorization is associated with surface learning where students should instead be working towards development of conceptual understanding of the concepts. Research data also reveal that students struggle with metabolic pathways reactions due to the lack of understanding of the mechanisms and arrow pushing steps involved in these reactions.

Students' perceptions about approaches to improve learning and understanding of metabolic pathways include: studying and drawing diagrams, taking the time to understand what is happening, creating mnemonics for enzymes and steps, looking at the big picture and understanding how the different steps fit together, and integrating demonstrations and activities into the instruction. It is noteworthy that students did not refer to active learning and inquiry based learning to promotes the development of conceptual understanding and improve learning of metabolic pathways. When biochemistry instructors utilize science education based learning, it helps students understand the conceptual aspects of metabolic pathways better because most undergraduate courses emphasize memorizing details and facts, which disconnects students from the principles of the phenomena.

Our research results and conclusions are based on data collected from a study that is limited by the answers we received in the survey. Interviewing a subset of students and asking them probing questions about specific challenges in learning about metabolic pathways and strategies that students rely on in learning these difficult concepts can provide additional invaluable information. Future work that elicits more detailed data and in depth interviews would make for a research study.

The implications of this research study is that teaching and learning of biochemical pathways should rely on science education research and utilize learning strategies that encourages conceptual understanding and deters students from reliance on memorization.

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