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Examining some of the challenges students face in learning about rearrangement reactions in organic chemistry

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ABSTRACT

Organic chemistry course is considered one of the most difficult courses students have to take as part of their academic science and engineering requirements. The purpose of this research project is to examine students' perceptions about the challenges they face in learning about rearrangement reactions and their approaches to improve their learning and performance in the concepts while learning organic chemistry. The research investigation took place at the City College of New York, a minority serving, commuter institute in an urban environment. The research participants were students who have completed at least one course of organic chemistry. The research instrument used in this investigation consisted of a questionnaire that was made up of Likert-scale and open-ended questions. The Likert-type questions were on a five-point scale that were converted into numerical, and the averages of the students' responses were taken. For the open-ended, the data was coded and compiled based on categories and similarities, converted into percentages and used to create bar charts. Our research findings suggest that students face challenges in learning about rearrangement reactions and their mechanisms and that relying on memorization and rote learning to solve them hinders the development of conceptual understanding. The data seem to suggest that students do not understand the significance of energy as a driving force in the transformations and pathways from reactants to products. Lastly, the data reveal that students lack the ability to apply the correct knowledge to solve problems involving rearrangement reactions and mechanisms, which inhibits their meaningful learning and conceptual understanding development.

Keywords: rearrangement reaction, organic chemistry, chemistry education research

INTRODUCTION

Chemistry is a language that allows us to interpret many situations that occur in our lives, in rational terms; it plays a huge role in integrating all sciences (Kornberg, 1987). It is critical in enhancing our understanding of the molecular level structure and how it relates to the behavior of physical, chemical, and biological systems (Cooper et al., 2010). Learning chemistry requires a deeper analysis at the microscopic, symbolic, and macroscopic level (Wang et al., 2022). This learning is what often challenges students as both the microscopic and symbolic levels are abstract and invisible naturally (Ben-Zvi et al., 1986; Mirzaie et al., 2010). Chemistry symbols do not simply convey transparent information but rather a detailed analysis on the microscopic and macroscopic level, which often confuses the learner (Taber, 2009).

Organic chemistry is one of the most challenging chemistry courses taught during undergraduate years (Garg, 2019). It is such an onerous course with attrition rates ranging 30-50% at some universities (Grove et al., 2008). It is a vast and continuing field that serves as a framework for science majors, engineers, and pre-medical fields. Therefore, the challenges students face with organic chemistry courses can impose difficulties in such career paths. Many of the difficulties students experience in learning organic chemistry occur as a result of relying on rote memorization rather than developing a cohesive understanding (Grove & Bretz, 2010; Grove et al., 2008). For learning to be effective, students should move beyond memorization and to develop a conceptual understanding of topics presented including nomenclature, resonance, acid-base reactions, mechanisms, and synthesis (Salame et al., 2019). Students come with the notion that if they have managed to excel in their general chemistry courses, they will be able to succeed in organic chemistry courses. However, students' success in chemistry classes is not always indicative of their performance in their organic chemistry courses (Anderson & Bodner, 2008). The language of organic chemistry involves complex themes; it is multifaceted; there are many unfamiliar words with Greek and Latin roots alongside technical vocabulary that are not in use outside of the school (Childs et al., 2015).

Chemistry curriculum places a challenge on students' learning due to the improper arrangement of topics in terms of difficulty levels (O'Dwyer & Childs, 2014). Researchers have found that some of the challenges students encounter may not be attributed to the subject itself but rather the way the information is presented, including misleading vocabulary or unfamiliar words within the textbook (Johnstone & Selepeng, 2001). Although most of the concepts in chemistry are not logically arranged, they do require a draw on previous knowledge as well as previously worked examples (Taber, 2001). Hence, students' misconceptions arise when they fail to link their initial knowledge from previous chemistry classes with their newly acquired knowledge upon entering higher education (Pinarbasi et al., 2009). Students simply attempt to memorize the newly acquired information without linking it to any previous knowledge and that is what causes the emergence of rote learning (Bretz, 2001; Grove & Bretz, 2012; Novak, 2002). This is in conjunction with what other researchers have found that students have disconnected ideas; they are able to memorize definitions but cannot use them in context (Anzovino & Bretz, 2016). Therefore, this necessitates the importance of higher order thinking tasks. If students are not engaged in higher order thinking tasks, they are less likely to adopt cognitive, more demanding reasoning modes (Christian & Talanquer, 2012).

Furthermore, students experience difficulties with naming that involves branched and substituted chains of alkanes, alkynes, dienes, and geometric isomers (Adu-Gyamfi et al., 2017). Their poor performance was noted especially with IUPAC naming that involves writing structural formulas of alkenes, alkynes, alkanols, alkanoic acids, and alkyl alkanoates (Adu-Gyamfi et al., 2013).

Mechanisms are considered one of the most important topics in organic chemistry yet are one of the most challenging topics for students (Graulich, 2015). The use of mechanisms requires a different set of skills in a more process oriented thinking including designing synthesis routes as well as deducing reasonable mechanisms (Graulich, 2015). Researchers postulated that students are not aware of the benefit of utilizing curved arrows in reaction mechanisms as a tool to predict the stepwise process towards the final product (Bhattacharyya & Bodner, 2005). Furthermore, students do not consider the feasibility of each step they wrote, but rather draw arrows that lead to electron pair and atom replacement associated with each product (Bhattacharyya & Bodner, 2005). The failure to properly use curved arrows in mechanistic tasks could be in part due to students' persistence on rote memorization rather than developing a cohesive conceptual understanding (Grove & Bretz, 2010, 2012). Also, students need to develop their mechanistic thinking more explicitly and identify patterns more clearly in organic reaction mechanisms (Galloway et al., 2019). In one research study, the author report that students struggled with proposing electron pushing mechanisms including errors related to formal charges, rearrangement, and arrows (Sunasee, 2022).

Undergraduate students majoring in chemistry, and one semester away from graduation, do not consider reaction mechanisms to be essential for product prediction (Bain & Towns, 2018). They have a deterministic thinking when deciding the right product of a reaction; they think solely about products with lowest energy or highest stability while ignoring the energetics of the pathways to reach the products (Bhattacharyya, 2014). This further indicates their lack of understanding of the importance of mechanisms to obtain the right product (Rushton et al., 2008). Moreover, when students were given two sets of nucleophilic substitutions reaction mechanisms to compare, predict the feasibility, and provide a rationale behind their approach, they did not use the highest mode of reasoning in explaining their approach; there was a missing gap in their conceptual understanding (Bodé et al., 2019). The inability to apply the correct content knowledge is what prevents students from developing reasonable reaction mechanisms (Ferguson & Bodner, 2008).

Alongside the importance of understanding the significance of each step in a reaction mechanism, it is critical to raise awareness of why reaction mechanisms and synthesis are used in organic chemistry in the first place; putting emphasis on their importance will promote meaningful learning (Raker & Towns, 2012a, 2012b). When asked to predict the major products involving either S_N1 reaction or elimination reaction, students were able to produce the correct structures but without fundamental understanding. Therefore, putting emphasis on understanding chemical concepts as well as applying it is critical in organic chemistry practices (Cruz-Ramírez de Arellano & Towns, 2014). Understanding the rationale behind reaction mechanisms will serve as a framework for synthesis related tasks. For instance, graduate students have found it helpful to use mechanisms as the groundwork for synthesis problem-solving and it was more beneficial to them than undergraduate years as these mechanisms allowed them to troubleshoot unexpected problems (Anderson, 2009). Furthermore, students need to develop an understanding of carbocation stability, which is an important part of mechanisms that involve rearrangement and cannot be separated from the topic (Kalsi, 2020).

Synthesis is another topic that impedes students' ability to succeed in organic chemistry. The key to an understanding of synthesis is dependent in part on how well a student draws electron pushing formalism, as mechanisms predict the selectivity of synthetic transformation (Ferguson & Bodner, 2008). Graduate students did not find chemical principles to be essential while solving synthesis problems (Bowen & Bodner, 1991). Moreover, students are unable to organize their thought process when approaching organic synthesis problems and they tend to rely on algorithmic rules without rationalizing their chosen synthesis route (Sevian et al., 2015). Therefore, having a variety of diverse exercises and problems that require higher order thinking skills of synthetic routes is required to foster students' knowledge; these activities could also be useful for students in applying chemical concepts in different problem contexts (Graulich, 2015). For instance, students can deduce the next step for a reaction mechanism by comparing pka values of functional groups (Graulich, 2015).

Acid-base reactions are one of the most important components of organic chemistry. They are the foundations for understanding elimination and substitution reactions involving acid-base chemistry. They are also foundational to electrophiles and nucleophiles that are defined using the Lewis model (Salame et al., 2020). The difficulties students encounter when distinguishing the different theories of acid-base reactions make it challenging for them to apply these theories into organic acid-base reactions (Bhattacharyya, 2006; Cartrette & Mayo, 2011; Cooper et al., 2012; McClary & Talanquer, 2011). For instance, identifying the nucleophile as Lewis base and electrophile as Lewis acid is what often causes students to experience difficulties distinguishing between a nucleophile and an electrophile, due to their inability to relate the functionality of either one of them to the accurate acid/base model–the Lewis model (Cartrette & Mayo, 2011). Understanding acid-base chemistry is critical as it is the groundwork for rationalizing a lot of reactions as well as organic synthesis. If students are unable to understand the nature of the reaction based on acid-base character, then they will face greater difficulties succeeding in organic synthesis (Salame et al., 2020).

Moreover, students have a poor understanding of Lewis structures; only few of them can explain the purpose of these structures in inferring chemical information, molecular shapes, and influence of intermolecular forces from it (Cooper et al., 2010). This poor understanding could be a result of the dominant principles learned in general chemistry or poor illustration of Lewis structures namely to convey shapes and properties (Cooper et al., 2010). Despite the fact that the rules for how to draw Lewis-structures are in almost every chemistry textbook, students are still struggling with such a task (Packer & Woodgate, 1991). For instance, when students are given the molecular formula for C_2H_6O, they have a variety of ways in how to arrange atoms of such a molecule regardless of the bonds or electrons (Packer & Woodgate, 1991). These students are less likely to produce a structure with the correct attachment of atoms, even for simple structures like CH_2O or $C_2H_4O_2$ unless they have come across these examples before (Packer & Woodgate, 1991).

Understanding acid-base reactions impose difficulties even at the graduate level. Graduate students struggle with understanding acid-base reactions; they rely mainly on bond polarizations to explain the weakening of bonds between the acidic hydrogen and its bonded atom (Bhattacharyya, 2006). Students fail to relate the acidity strength to the structure of the entire molecule as well as neighboring molecules present in the solution (Salame et al., 2020). Even when students are aware of the different factors that contribute to acidity strength, they are less likely to rationalize their effects on acidity. For instance, resonance is one of the factors students attribute to acidity strength, but they do not have a grasp of how and why the conjugate base of many resonance structures are more stable (McClary & Talanquer 2011).

Structural representations are essential in the chemistry field especially in the nature of chemistry practice (Kozma et al., 2000). These are needed skills for understanding the rationale behind the chemical phenomenon underlying physical entities (Kozma & Russell, 2005). In the context of Lewis structures, these important fundamentals for meaningful understanding of such a concept are eliminated by the institutions themselves (Kozma & Russell, 2005). As a result, students experience difficulties drawing the right structures if they were presented to them differently or if the molecules increase in complexity (Cooper et al., 2010). They also encounter difficulties with the function and syntax of chemical formulas; they rely on chemical formulas as abbreviations instead of inferring chemical composition from them (Taskin & Bernholt, 2014). They consider symbols to be letters, numbers, and lines on a page unless they represent physical reality to them (Bodner & Domin, 2000).

Students have a lack of understanding of the properties of atoms and molecules causing them to struggle with applying pH and pK_a values to various contexts (Nakhleh & Krajcik, 1994). They are not able to find and estimate pK_a values, which is a great skill to possess especially when trying to decipher complex chemistry reactions that do not provide these values (Flynn & Amellal, 2016). Students often correlate stronger acids with having a higher pH level (Ross & Munby, 1991). This indicates they lack conceptual understanding of these concepts as they will not be able to apply these concepts to unfamiliar contexts.

Students also have a lack of understanding of the concept of polarity. They think that polar compounds are capable of forming hydrogen bonds (Schmidt et al., 2009). Some students believe that the ability of organic compounds to boil is based on the presence of covalent bonds within these molecules and that hydrogen bonds can form when there are hydrogen and oxygen atoms (Schmidt et al., 2009). Furthermore, they do not have a solid understanding of intermolecular forces as an interaction between neighboring molecules (Cooper et al., 2015). Students understand intermolecular forces in the context of polarity and solubility but are unable to identify reaction sites within natural products (DeFever et al., 2015).).

Chirality and stereochemistry are challenging topics to organic chemistry students, leading them to advance to the next topic without having a conceptual understanding of them (Chapman & Russell, 1992). Students experience difficulties understanding, interpreting, and translating structural representations due to content gaps or lack of visuospatial skills, especially rotations (Shubbar, 1990; Tuckey et al., 1991; Wu et al., 2001). For instance, when determining the stereochemistry of enantiomers defined by Cahn-Ingold-Prelog R/S designation, students rely on their mental rotation of given objects and molecules; such a task can get sophisticated as molecules increase in size with different stereocenters (Stieff, 2007). Moreover, relying on mental rotation in determining the stereochemistry of structures is time-consuming (Stieff, 2007). Although molecular models are available for students and are beneficial when dealing with tasks like rotations, students rarely use them (Stieff et al., 2016). As a result, students end up assigning the wrong R/S designation to the molecule, which causes alteration of the stereochemistry of the molecule.

One of the reasons students face greater difficulties representing molecular images is due to the rules or principles learned in general chemistry that are not covered again in depth in organic chemistry classes (Ealy & Hermanson, 2006). Therefore, manipulating and translating between molecular formulas and structural representations can be overwhelming for them (Kozma & Russell, 1997). Students face difficulties placing substituents in the right position either axial or equatorial when dealing with chair conformations, which alter the stereochemistry of the molecule (Mistry et al., 2020). They also struggle with drawing the correct orientation of the three groups attached to the front or back carbon in Newman projections and this leads to incorrect stereochemistry of the whole molecules (Mistry et al., 2020).

Students encounter difficulties with the three-dimensional nature of molecules (Gilbert, 2005; Uttal & O'Doherty, 2008). They found it difficult to convert from two-dimensional structures to three-dimensional structures due to the lack of knowledge in three-dimensional visualization (Gilbert 2005; Uttal & Doherty 2008). Moreover, this lack of understanding can impede their efficiency in their problem-solving behavior (Bodner & Domin, 2000). Therefore, students need to adopt experts' type of thinking when approaching stereochemistry related tasks.

Experts are able to draw connections from various representations and coordinate their features to support reasoning of any physical or chemical processes underlying them, while novice students are incapable of manipulating multiple representations during problem solving (Kozma et al., 2000). Students struggled with converting Dash-Wedge structures to Newman projection; their performance decreased as the complexity of degree of rotations in Newman projection increased (Kumi et al., 2013). The ability of students to translate from Dash-Wedge structures to Fisher projection is directly related to the conformation and spatial arrangement of substituents on the Dash-Wedge structures (Kumi et al., 2013).

Resonance lays the groundwork for rationalizing most of organic chemistry topics including reaction mechanisms, conjugation, aromaticity, spectroscopy, product distribution, and many more (Carey & Sundberg, 2007). This topic imposes a lot of difficulties for students because succeeding in most of the topics depends on having a conceptual understanding of it. Students encounter difficulties conceptualizing resonance; they think of resonance as alternating structures between different states just like in the case of benzene ring (Taber, 2002).

Surprisingly, this topic has also caused a lot of misconceptions for chemistry teachers. Pre-service chemistry teachers think that resonance structures are two or more of Lewis structures but with a difference in arrangement of atoms and electrons; they also think that there is no correlation between formal charge and resonance structures (Widarti et al., 2017). Similarly, students face difficulties with electron delocalization as the number of atoms exceeds the one atom dimension they are used to in their general chemistry classes (Ealy & Hermanson, 2006). Furthermore, they experience difficulties determining if presented structures are aromatic as they focus mainly on certain atoms and the octet rule while disregarding delocalization (Ealy & Hermanson, 2006). Yet students have a good grasp of electronegativity as they explain the shielding effects in an NMR spectrum (Ealy & Hermanson, 2006).

Reaction coordinate diagrams are great assets for students that help them visualize energy changes during chemical reactions (Allinger, 1963; Meek et al., 2016). Students can infer from the reaction coordinate diagrams information about thermodynamic and kinetic products involved in the transformation of chemical reactions (Allinger, 1963; Meek et al., 2016). However, energetics associated with chemical reactions is still a challenging topic for students (Raker et al., 2013). Students face challenges in interpreting the surface features including peaks, valleys, peak heights, and peak width (Popova & Bretz, 2018). They also encounter difficulties understanding energy changes associated with the transformation of reactants into products (Bhattacharyya & Bodner, 2005; Tastan et al., 2010).

It has been reported that students seem not to understand the physical processes underlying the transformation of reactants into products; they chose to focus more on individual structures rather than the mechanism overall (Bhattacharyya & Bodner, 2005). This necessitates the input of instructors to help students transition from focusing on independent reaction species to consider the least energetic reaction pathway (Bhattacharyya & Bodner, 2005).

Students have misconceptions about the kinetics of reaction mechanisms. They think that an increase in temperature will cause an increase in activation energy, inability to recognize the slowest step as the rate determining step, and a catalyst causes the activation energy to go up (Calik et al., 2010; Kolomuc & Tekin, 2011; Tastan et al., 2010). They also conflate intermediates and transition states even after giving the correct definition of both (Popova & Bretz, 2018). Instructors also face difficulties deciphering reaction coordinate diagrams. For example, Turkish pre-service teachers are able to give the correct definition of an intermediate but cannot highlight the location of the intermediate in a reaction coordinate diagram; they also confuse ideas of activated complex and an intermediate (Tastan et al., 2010).

Guiding Research Questions

1. What are the learning challenges that students experience in learning about rearrangement reactions?
2. What approaches do students use when solving reactions that involve rearrangements?
3. What rationale do students adopt when it comes to understanding carbocation stability?

METHODS

The purpose of the research project is to examine students' perceptions about the challenges they face in learning about rearrangement reactions and their approaches to improve their learning and performance in the concepts while learning organic chemistry. The investigation took place at the City College of New York during the Fall of 2021 and Spring of 2022. The City College of New York is an urban, commuter, minority-serving institute. The research participants were selected because they were either enrolled or had completed at least one semester of organic chemistry. The participants were from different sections of organic chemistry I and II, as well as biochemistry courses. It is noteworthy that organic chemistry is a standard course offered in the traditional way of teaching: lecture. The research instrument used in this investigation consisted of a questionnaire that was made up of Likert-scale and open-ended questions.

The questionnaire, which was comprised of six Likert-type and seven open-ended questions, was examined by two faculty

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

Likert-type question	Average answer from respondents
I struggled with learning about rearrangement reactions.	3.46
Rearrangement reactions are a difficult part of organic chemistry.	3.55
I am unsure when I should perform rearrangement.	2.76
Carbocation stability plays a large part of solving rearrangement problems.	4.24
I struggled with solving rearrangement problems.	3.44
Memorization is very important for solving rearrangement problems.	3.18

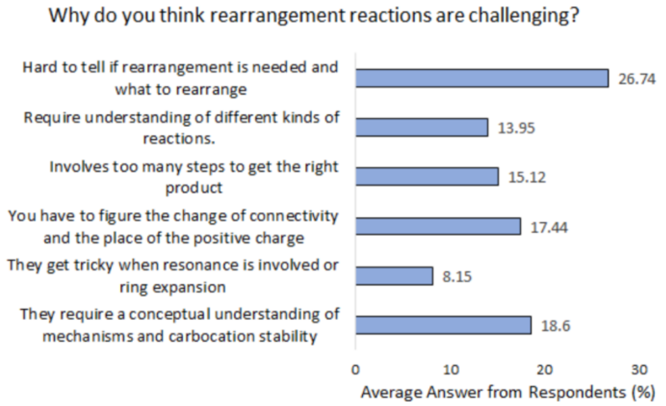

Figure 1. Bar chart depicting students' perceptions about challenges that students face learning about rearrangement reactions (Source: Authors' own elaboration)

members in science education, at the City University of New York, who agreed that the questions adequately capture the investigation about challenges in learning about organic chemistry rearrangement reactions. The use of the test-retest approach provided a reliability coefficient of 0.8 through testing and retesting method. A total of 81 students participated in completing the questionnaire.

The Likert-type questions were on a five-point scale that were converted into numerical values, as follows: strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5). We chose the Likert-scale type of questionnaire because it is one of the most commonly used as a psychometric data collection tool (Wakita et al., 2012) due to its ease of use by the respondents, convenience of construction, the generation of statistical data with high reliability, and its efficiency (Li, 2013). The averages of the students' responses were taken. A single factor ANOVA was performed on the Likert-type questions found $p<.001$. p-value<0.05, which is strong evidence against the null hypothesis and shows that there is a strong relationship between the variables. Furthermore, the mean square for our data is 19.17, which is much larger than the mean square within the treatments, which is 0.97. This value is large enough to confidently reject the null hypothesis.

For the rest of the questions, open-ended, we collected the data, compiled the answers based on categories and similarities, converted them into percentages, and used it to create bar 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.

RESULTS AND DISCUSSION

According to the results shown in **Table 1** and obtained from the Likert-scale questions, students seem to be facing difficulties learning about rearrangement reactions and that they consider them to be a difficult part of organic chemistry. Additionally, the data suggests that students consider carbocation stability an integral part of solving organic chemistry mechanisms and reactions that involve rearrangement. Memorization, as the data suggests, is considered a critical part when solving rearrangement reactions. The data also indicates that students seem to be neutral when deciding if they should perform rearrangement. These factors, among others, are what causes students to struggle when solving rearrangement reactions, which is also supported by the data. Overall, students seem to have the perception that rearrangement reactions are a difficult part of organic chemistry, as they struggle with these reactions and in understanding the carbocation stability in these mechanisms and reactions problems. These findings are supported by research in the field that reports that students find mechanisms challenging to learn and master in organic chemistry (Graulich, 2015). Furthermore, studies in the field report that students seem to rely on memorization instead of conceptual understanding for solving rearrangement-related problems, which is consistent with other research findings in the field of chemistry education research (Grove & Bretz, 2010). This is consistent with our findings and further supports our research.

The results obtained from one of the open-ended questions about students' perceptions about what makes rearrangement related mechanisms and reactions are presented in **Figure 1**. According to results, about 27% of students are encountering difficulties spotting rearrangement reactions and deciding what they should rearrange, which could be attributed to the lack of a well-developed conceptual understanding of the concept and low self-confidence about dealing with organic chemistry related problems. 17.4% of participants report that when performing rearrangement reactions, they face challenges with visualizing the change in connectivity and the location of the positive charge. This suggests that students struggle in understanding the structure and its connectivity and translating between molecular formulas and structural representations, which can inundate students (Kozma & Russell, 1997). Also, 8.2% of students suggest that rearrangement reactions are difficult when resonance and ring expansion are involved. Resonance is an important concept in learning about organic chemistry and plays a significant role in learning of many topics of organic chemistry and students' learning of topics can depend on development of conceptual understanding of resonance (Carey & Sundberg, 2007).

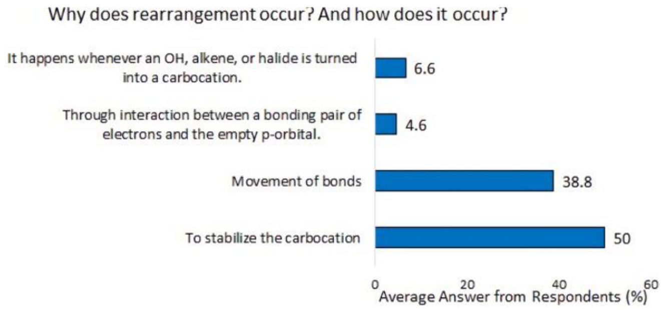

Figure 2. Bar chart representing some of the explanations that students provide about explaining reasons for rearrangement reactions and the process of reactions (Source: Authors' own elaboration)

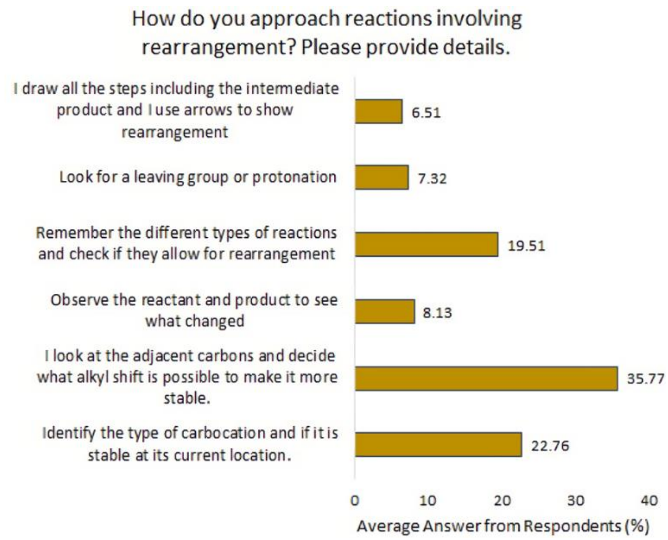

Figure 3. Bar chart representing percentage responses from participants on approaches they use in solving rearrangement reactions (Source: Authors' own elaboration)

Furthermore, 15.1% of students think that rearrangement reactions are convoluted, as they require too many steps to get right product, and 14.0% of students think that rearrangement reactions require understanding of different types of reactions. Lastly, 18.6% of research participants think rearrangement reactions are overwhelming as they require conceptual understanding of mechanisms and carbocation stability.

Figure 2 is a bar chart depicting students' explanations for the reasons rearrangement reactions occur and the driving force for this phenomenon. The data from the students suggest that 50% of students believe that rearrangement reactions occur to stabilize a carbocation, 5% of students think that rearrangement reactions occur through interaction between a bonding pair of electrons and the empty p-orbital, and another 7% of students think that rearrangement happens when an alcohol, alkene, or a halide is turned into a carbocation. Understanding what is taking place at each step in a mechanism and the driving force for it is of significant importance to the learning of organic chemistry. This is in conjunction with other research findings that underscore the importance of understanding each step in a reaction and mechanism to promote meaningful learning (Raker & Towns, 2012a, 2012b). Furthermore, almost 39% of students have the perception that rearrangement occurs through the movement

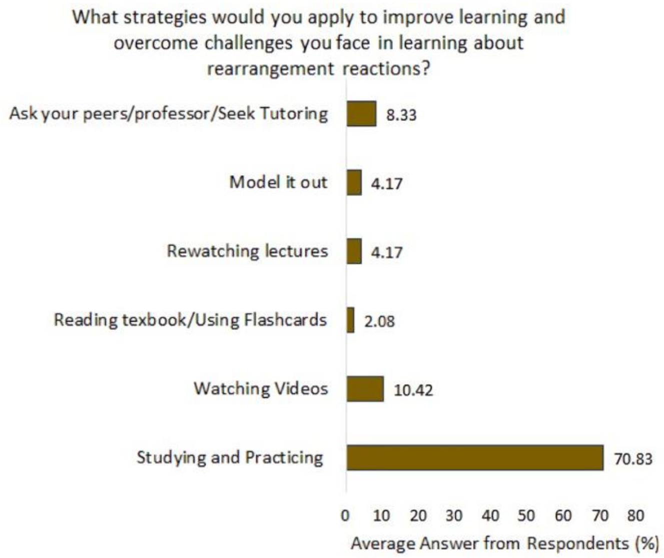

Figure 4. Bar chart depicting students' perceptions about strategies that they employ to improve learning of rearrangement reactions (Source: Authors' own elaboration)

of bonds. This shows that students do not appreciate the role or importance of energy changes associated with the reactions and their mechanisms, which has been reported by researchers in the field (Tastan et al., 2010).

The results obtained from another open-ended question about students' using approaches to solve rearrangement related reactions and mechanisms are presented in **Figure 3**. Our data shows that 36% of participants would examine the adjacent carbons of a carbocation to determine what can be shifted, and 23% examine the stability of the carbocation to decide whether rearrangement is possible in a reaction. Furthermore, about 20% of participants rely on memorization and rote learning by recalling the types of reactions that would often involve rearrangement. This might create an obstacle to development of conceptual understanding and meaningful learning. It will also cause additional problems to learn, since memorization does not equate with meaningful learning or conceptual understanding, which is supported by research in the field of science education (Grove & Bretz, 2010, 2012).

A fraction of students believe that it is helpful to observe the reactant and product to visualize what has changed, suggest that looking for a leaving group or protonation is a useful way when approaching rearrangement reactions, and think that it is beneficial to draw all the steps including the intermediate products and using arrows to show rearrangement. Students seem to lack the capacity to apply the correct knowledge in approaching rearrangement reactions, which could hinder their development of conceptual knowledge about reaction mechanisms, and this is congruent with other research findings (Ferguson & Bodner, 2008).

Figure 4 presents data on strategies that students employ to improve learning about rearrangement reactions. Majority of them, 71%, report that studying and practicing is strategy they would use to improve learning and overcome challenges of rearrangement reactions. To develop understanding of chemistry concepts, researchers in science education suggest that students need to integrate varied components that are multifaceted in nature (Orgill & Bodner, 2007).

The rest of participants suggest that asking their peers, professors, and tutors for help when encountering difficulties, watching YouTube videos to cover any content gap they might have, re-watching the lecture videos to gain a better understanding of the materials, reading the textbook and creating flashcards, and building molecular models to improve learning of rearrangement reactions.

CONCLUSIONS

Students face challenges in learning about rearrangement reactions and their mechanisms during their studies of organic chemistry and rely on memorization and rote learning to solve rearrangement reactions, which could hinder the development of conceptual understanding and meaningful learning. Students seem to identify several factors that present obstacles to learning about rearrangement reactions and their mechanisms, which include recognizing rearrangement reactions and where the arrangement takes place, visualizing the change in structure and the location of the positive charge, and discerning resonance and ring expansion involved during rearrangement. Furthermore, our research findings suggest that students struggle with rearrangement reactions and their mechanisms because of the myriad number of reactions and their mechanisms involved and find it overwhelming to understand.

Students have alternative conceptions about rearrangement reactions, which include their beliefs that rearrangement reactions occur to stabilize a carbocation and that rearrangement occurs through the movement of bonds. Additionally, the students do not understand the significance of energy as a driving force in discussing rearrangement reactions and mechanisms. Students' report that the reasons for forming a less stable carbocation could be due to resonance stabilized formed structure, ring expansion, certain types of substitution and addition reactions. However, students do not discuss the role and importance of energy changes associated with such transformations and pathways from reactants to products, which could lead us to believe that students do not possess a well-developed conceptual understanding of energy consideration and their impact during a chemical reaction.

Students' approaches and reliance on rote learning and memorization can hinder students' abilities to develop conceptual understanding and meaningful learning of the concept of rearrangement. Furthermore, participants' responses suggest that they lack the ability to apply the correct knowledge to solve problems related to rearrangement reactions and mechanisms, which inhibits their meaningful learning and understanding. Instructors should nurture the development of conceptual understanding of arrow-pushing formulism in organic chemistry teaching and provide students with learning opportunities that allow them to learn meaningfully about the concepts.

A future study can include other institutions that focuses on more detailed data and students' interviews to gain insight into their thinking about approaches to mechanism problems that involve rearrangements would be the next steps to this article.

Limitations

There are a few limitations to our study, as follows:

(1) The data in this study was collected from one urban, minority serving institution, where the students come from a wide range of backgrounds, and we did not account for this in our data analysis. A similar research study with data collected from several different institutions could provide valuable insights and build the findings of this study.

(2) We did not address students' conceptual understanding or acids and bases, nucleophiles and electrophiles, and students' perceptions about electron pushing formulism, which are instrumental for students' learning of mechanisms and rearrangement reactions. These can be addressed in future studies.

(3) Mechanisms that involve rearrangement are quite complex as a topic and to study. It can be arduous to obtain enough detailed data and insights on students' perceptions and views about the challenges in the topic from a questionnaire and short interviews. More detailed data and in depth interviews would make a reasonable future study.

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Ethical statement: Authors stated that the investigation and survey administration and collection were performed in accordance with the Internal Review Board (IRB).

Declaration of interest: No conflict of interest is declared by authors.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

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