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ORIGINAL ARTICLE

Unmasking Approaches and Errors to Synthesis-Type Problems: Insights from Undergraduate Chemistry Students

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ABSTRACT

This study aimed to uncover common difficulties and possible areas for improvement by focusing on the approaches and errors made by 3rd-year undergraduate chemistry students in solving organic synthesis problems. The study employed a purposive sampling technique to select 112 undergraduate chemistry major students to participate in this study. Students' responses to synthesis-type problems from mid-semester examinations within the framework of a synthetic methodology course in a Ghanaian University were examined. The primary data collection tool was a mid-semester examination that employed deductive coding systems to analyze students' responses. The study's findings revealed that while many students performed well in identifying and providing reagents for the given reactions, a lot more struggled with other types of synthesis problems. Specifically, the reaction mechanism-type questions recorded the lowest scores and most errors among the synthesis problems. A significant number of students (67.0% and 66.1%, respectively) encountered difficulties in drawing complete reaction mechanisms and proposing the synthesis of target molecules, respectively. The results further indicated that students may have relied on rote memorization in solving synthesis problems. Students' significant errors included the inability to draw resonance structures, expand atoms/bonds, map atoms, generate starting material/chemical equivalent, and draw correct products. However, students showed glimpses of using retrosynthesis analysis through the disconnection approach and exhibited a good usage of arrows in arrow-pushing formalism. The study recommends focused interventions and teaching strategies to enhance students' understanding of reaction mechanisms, drawing of resonance structures, expanding atoms/bonds, mapping of atoms, starting material generation, and problem-solving skills in organic synthesis. Besides, students should be provided with ample practice for synthesis design by educators.

KEY WORDS: Errors; organic synthesis; reaction mechanisms; synthesis-type problems retrosynthesis; undergraduate chemistry major students

INTRODUCTION

Solving synthesis questions, in which students must apply their knowledge of chemical principles and processes to come up with a plan for synthesizing a target molecule, is one of the most challenging tasks in organic chemistry education (Anderson, 2009). Mostly, the number of synthetic steps required to produce the desired product equals the number of reactions carried out (Salame et al., 2020). To solve synthesis-type problems, students must understand the relationship between molecular structures, reagent function, and the reaction mechanism involved (LaFarge et al., 2014). That is, in solving synthesis-type problems, students must visualize the target molecule, understand how reagents react with the starting material to afford the key transformations, and correctly sequence them (Flynn, 2014). Therefore, answering synthesis-type problems demands more than just rote memorization of specific steps. Many chemistry textbooks recommend the "retrosynthetic or disconnection approach" as a synthesis strategy but lack hands-on methods for mastering organic synthesis (Bruice, 2014).

Retrosynthetic analysis or the disconnection approach is one of the recommended problem-solving approaches in organic synthesis. This approach involves working backward from the target molecule to identify the necessary starting materials and the sequence of reactions required to synthesize the desired compound. For students, retrosynthetic analysis or working backward poses serious conceptual difficulties (Parsons, 2019). Performing a retrosynthetic analysis is difficult since it calls for understanding a vast array of known organic reactions in addition to the ability to visualize the experimental setups required to give a desired product (Starkey, 2018). Lack of knowledge of reactions and the skill of selecting the correct reaction can impede students' ability to solve synthesis problems. According to Graulich (2015), students often lack the implicit knowledge necessary to comprehend how to apply concepts and models to various tasks, and they are unable to transfer much of their general chemistry knowledge into organic chemistry courses. A study conducted by Flynn (2014), on how students work through organic synthesis learning activities suggested that students who relied on familiarity with the reactions were able to determine how a specific bond could be made. On the contrary, students who could not recognize reaction types did not know how to make a specific bond. In another study reported by Bodé and Flynn (2016), they maintained that students' knowledge of reactions alone is not enough to be successful in designing the synthesis of a target molecule. Particularly, they observed that most students exhibited knowledge of reactions but were unable to use that knowledge effectively.

Again, solving synthesis-type problems requires a deep knowledge of reaction mechanisms by the organic chemist to break apart a target molecule. Reaction mechanisms provide insight into how reactions occur at the molecular level, including the movement of electrons and the formation and breaking of bonds. Understanding reaction mechanisms helps to predict the outcomes of reactions and select appropriate reagents. According to Ferguson and Bodner (2008), mechanisms play a key role in predicting the selectivity of synthetic transformations, and therefore, how well a student draws these curved arrows is highly indicative of their success in responding to synthesis problems. Studies have shown that graduate students who learned to use reaction mechanisms as the foundation for their synthesis problem-solving improved significantly and discovered that mechanisms are even more helpful now than they were when they were undergraduates because mechanisms helped them tackle unforeseen issues (Anderson, 2009). Unfortunately, due to inadequate understanding of reaction mechanisms, many students only reproduce memorized sequences of events when approaching synthesis problems rather than using reaction mechanisms to explain their process (Ferguson and Bodner, 2008). Consequently, a lot of students often struggle with not knowing where to begin and selecting proper pathways during retrosynthesis analysis. In most cases, students usually find it challenging to approach synthesis problems systematically, which makes it difficult for them to choose the right reagents and reactions (Bodé and Flynn, 2016).

Some approaches or strategies used by students in tackling synthesis-type problems have been reported in the literature. For instance, Flynn (2014) reported that, in working through synthesis problems, students showed desirable problem-solving skills, including utilizing reaction mechanisms and chemical principles. However, they avoided some questions when they could not remember the answer. Sometimes, they relied on familiarity without using a problem-solving strategy. According to a study on students' strengths, strategies, and errors when using the electron-pushing formalism (EPF) by Flynn and Featherstone (2017), only a few of the students employed strategies such as expanding or mapping structures in problems involving reaction mechanisms. Mapping atoms and bonds involves identifying which atoms in the reactants correspond to those in the products and understanding how bonds are formed or broken during the reaction. This strategy helps to visualize the synthesis pathway and ensure that all necessary components are accounted for. Another study on strategies of successful synthesis solutions reported by Bodé and Flynn (2016) indicated that students' successful solutions exhibited key strategies including identifying newly formed bonds, adding atoms, and key regiochemical relationships, and mapping starting material atoms onto the target molecule. They also included partial or complete retrosynthetic analysis and drew reaction mechanisms.

Problem-solving is central to the field of organic chemistry, making the ability to solve synthesis problems a vital skill that requires continuous careful examination (Bodé, 2018). This present study reports students' approaches to solving synthesis-type problems (i.e., identifying reactions, providing reagents, mechanisms, and proposing the synthesis), including errors, difficulties, and success rates in a Ghanaian university. The study was done to provide instructors with valuable perspectives on students' approaches, difficulties, and possible avenues for improvement in organic synthesis, which would, in turn, assist in improving instructional techniques and maximizing learning outcomes in organic chemistry education.

Research Questions

The following research questions guided the study:

1. What are students' success rates in answering synthesis-type questions?
2. What are the main approaches and errors students typically make while answering synthesis-type questions?

Theoretical Framework

The theoretical framework for this study is based on Ausubel and Novak's theory of meaningful learning. The theory of meaningful learning contrasts with rote learning and describes specific criteria for achieving meaningful learning (Novak, 1993). First, for meaningful learning to occur, learners need prior knowledge to serve as a foundation to build upon and integrate new information into existing knowledge frameworks. This new information or knowledge must be perceived as relevant and must include significant concepts and propositions. Moreover, learners are required to consciously make meaningful connections between new and relevant pre-existing knowledge (Bodé, 2018). The constructivism theory also postulates that knowledge and understanding are constructed in the mind of the learner through experiences that can be meaningfully connected with their prior knowledge and understanding (Bodner, 1986).

Organic chemistry relies heavily on problem-solving. Literature report suggests that crucial characteristics that differentiate between successful and unsuccessful problem-solving in organic chemistry include correctness, abstractness, and completeness of the representations that the problem-solver constructs (Domin and Bodner, 2012). In addition, these constructs might show how much conceptual knowledge a person brings to a problem-solving scenario. To be able to solve problems, learners need to apply their prior knowledge and conceptual frameworks (such as schemas, mental models, and theories) concerning the task at hand to identify relevant details, comprehend the issue, and generate possible solutions. The conceptual frameworks provide a structured approach to understanding complex information and relationships (Novak, 1993). One major barrier to solving problems is the quality of the frameworks used for integrating knowledge (Novak, 1990).

Organic chemistry, especially organic synthesis with its unique peculiarities is a whole new world to the students (Webber and Flynn, 2018). Consequently, inexperienced students may not be able to integrate their pre-existing knowledge with the appropriate frameworks and thus, may struggle to develop appropriate meaningful learning (Bhattacharyya and Bodner, 2014). By unmasking students' approaches to synthesis problems, instructors can appreciate how learners link their prior knowledge and the appropriate conceptual frameworks in solving synthesis problems. To this end, instructors can leverage the information obtained to better assist learners in preparing themselves for future synthesis problems they may encounter to maximize learning outcomes.

METHODOLOGY

Setting and Course

This study was carried out in the synthetic methodology course at a University in Ghana. Synthetic methodology is offered as the fifth organic chemistry course in the first semester of students' 3rd-year studies. The course was taught in English, and over the course of 12 weeks, students attended one 2-h lecture session, 1-h tutorial session per week as well as 2-h laboratory experience. Assessment for the course comprised two quizzes, a mid-semester examination, a group presentation, and a final examination. The course is designed to help equip students with skills and principles in designing synthetic schemes to synthesize simple but valuable organic compounds. Retrosynthetic analysis through the disconnection approach and functional group interconversion is the basis for formulating synthetic schemes for these organic compounds. Synthesis of target molecules relates to previously taught reactions while emphasizing the mechanistic organization of new reactions that may be required to synthesize a particular target molecule. Monofunctional, difunctional, and five- and six-membered rings are the major target molecules of interest.

Research Design

The research design for this study was a descriptive case study (Yin, 2014) that focused on unmasking students' approaches and errors in solving problems involving organic synthesis.

Sample and Sampling Procedure

A total of one hundred and twelve (112) 3rd-year Chemistry major students who registered for the Synthetic Methodology course comprised the sample for this study (census sampling). The class consisted of 100 males and 12 females with an average age of 22 years. These students were purposely chosen based on their prior completion of the required organic chemistry courses, which included functional group chemistry, chemistry of hydrocarbons, reaction mechanisms, and stereochemistry, and thus, possessed the relevant prerequisite knowledge. Moreover, this 3rd-year class was selected for this study because the author taught the Synthetic Methodology course.

Instrumentation

The main instrument used for data collection in this study was a mid-semester examination that consisted of three major items on identifying and providing reagents, drawing reaction mechanisms, and proposing synthesis of target molecules (Appendix 1). The mid-semester examination comprised questions on identifying reactions, providing reagents, drawing reaction mechanisms, and proposing synthesis for target molecules. The questions on the identification of reactions and the provision of reagents were centered on redox, aldol condensation, and the Wittig reactions. Participants were tasked to identify a reaction and provide the reagents required to achieve such transformation. Furthermore, the draw reaction mechanism-type question sought to examine students' ability to draw reaction mechanisms based on the Micheal addition and the Wittig reactions to predict the desired product. Proposing a synthesis for target molecules questions required students to propose the synthesis of a target molecule without a given starting material and also with a given starting material. The questions were based on the Wittig, and Claisen followed by an alkylation reaction. The examination was administered to the students to examine the approaches and errors that undergraduate students make in solving synthesis-type problems to guide educators on the instructional strategies and areas to emphasize in teaching the synthesis of organic compounds.

Validity and Reliability

The questions were given to two colleague instructors, who are experts in organic chemistry for moderation to examine their validity (face and content validity). To establish test reliability, two colleague experts in organic chemistry analyzed 15% of the student's responses independently using a prepared marking scheme. The agreement between the two independent assessments was 98%.

Ethical Considerations

To address ethical concerns associated with the dual role of both the researcher and the instructor, the researcher took the following ethical considerations. Permission was sought from the head of the Chemistry Education Department of the University to undertake this research. The student participants in this study were made to sign an informed consent form and were allowed to specify whether or not they wanted their responses to be used in the research. Furthermore, the students were made aware that their participation in the study was voluntary and that non-participation in the study would not affect their grades. In addition, pseudonyms were used instead of participants' real names when discussing or quoting their responses in this article. Using pseudonyms ensures that data analysis or reporting does not reveal individual student performance or responses.

Data Collection and Analysis Procedure

Data sources included answers to questions from mid-semester examinations of the first semester of the 2022/2023 academic year. These data sources are summarized in the appendix section (Appendices 1 and 2). Students were given a maximum of 80 min to respond to the items. Students' responses to the questions were graded by the researcher using a researcher-made marking scheme, and their scores were recorded on paper. A colleague's organic chemistry instructor verified that the scores were assigned according to the marking scheme (checking for grading errors and consistency) by comparing the assigned score to the same marking scheme. The assessment criteria for the synthesis-type questions were based on the ability of the students to use various strategies such as retrosynthesis analysis through the disconnection approaches, expanding bond/atoms, mapping of atoms, drawing of resonance structures, drawing starting materials, arrow usage, and many others in designing synthesis of a target molecule.

Data Analysis

Each question was carefully coded by the researcher and verified by a colleague expert to identify the most common approaches and errors that were exhibited in the answers. Analysis of students' responses to the questions was based on coding systems adapted from Flynn and Featherstone (2017). Students' responses were classified into "all required," "some required," and "not provided." All required meant that the student provided the expected answer in full and some required meant the student provided some or a part of the expected answer. Not provided meant that the students did not provide any answer required to the question. Students' responses were further categorized and presented as frequency tables and charts for discussion. Details of the coding system used for this study are provided in (Appendix Table A1). Scores in the range of 0–10 were classified as below average and 11–20 as above average.

RESULTS AND DISCUSSION

Students' Scores on Synthesis-Type Questions

Students' scores on the various synthesis-type questions were summarized and presented using a frequency table. Table 1 shows the scores of students on the various synthesis-type questions.

From Table 1, students obtained higher scores in identifying reactions and providing reagents-type questions than any other synthesis-type questions. For instance, nearly 94% of the students in this study obtained average or above scores (10–20) on this question. On the contrary, a large number of students struggled with the other synthesis-type questions. Particularly, 67.0% and 66.1% of students obtained average or below average (0–10) in the reaction mechanism and proposed the synthesis-type questions, respectively. The results revealed clearly that there is a gap between students' knowledge of reactions and their application to synthesis. According to Bodé and Flynn (2016), knowledge of reactions alone is insufficient to successfully propose the synthesis of target molecules. In other words, students lacked the critical skills needed to integrate their knowledge of organic reactions to design the synthesis of a target molecule (Graulich, 2015). However, for students to be successful in designing synthesis, they must be able to integrate several aspects of their knowledge in organic reactions (Biggs and Collis, 1982; Biggs and Tang, 2007). Unfortunately, many instructors fail to impart to their students the ability to integrate their knowledge of chemical principles, reactions, and skills to propose the synthesis of a specific target molecule from a specified starting material (Bodé et al., 2019).

Table 1: Students' scores on the synthesis-type questions

Scores	Question-type Identify reaction and provide reagents (%)	Reaction mechanism (%)	Propose a synthesis (%)
0–5	7 (6.3)	20 (17.9)	5 (4.5)
6–10	9 (8.0)	55 (49.1)	69 (61.6)
11–15	39 (34.8)	22 (19.6)	23 (20.5)
16–20	57 (50.9)	15 (13.4)	15 (13.4)

One of the skills required in making a sound synthesis of a target molecule is the ability to select reactions with reasonable reaction mechanisms. According to Ferguson and Bodner (2008), mechanisms are crucial in predicting the selectivity of synthetic transformations. Therefore, the ability of a student to draw these curved arrows accurately is an excellent indicator of their success in solving synthesis problems. As mentioned earlier, in Table 1, nearly the same number of students (i.e., 67% for reaction mechanism and 66.1% for proposing the synthesis-type questions) obtained low scores (average or below) in the reaction mechanism and proposed synthesis-type questions. These results indicate that students' difficulties in proposing plausible reaction mechanisms may have affected their ability to select the appropriate reactions to propose the synthesis of a target molecule. The results align with the observation of Anderson (2009) that students who learned to use reaction mechanisms as the foundation for their synthesis problem-solving improved significantly and discovered that mechanisms are more helpful because mechanisms help them tackle unexpected problems.

Students' Errors in Identifying Reactions and Providing Reagents-Type Questions

The synthesis-type questions on identifying reactions and providing reagents were aimed at evaluating students' proficiency in organic reactions, as a deep knowledge of organic reactions empowers students to select the relevant reactions for strategic planning in organic synthesis. Interestingly, all students attempted these questions, and most students (> 85%) identified the various reactions accurately. Some low scores recorded in this type of question were mainly due to the inability of some students to give the correct reagents for some of the reactions identified. In this regard, students' common errors included missing reagents, wrong reagents, and wrong ordering of reagents where the reaction required directed synthesis. Even though these observed errors may be relatively minor, they validate the assertion that students may have only memorized the reactions without meaningful understanding. However, it takes more than memorizing reactions to succeed in organic synthesis. Literature reports suggest that learning in organic chemistry is hampered by students' propensity to memorize rules and reactions (Anderson and Bodner, 2008; Grove and Bretz, 2012).

Students' Approaches and Errors on Reaction Mechanism-Type Questions

Students' answers to problems involving reaction mechanisms were analyzed to identify the approaches they used and any errors made. Figure 1 shows approaches utilized by students in their responses to the reaction mechanism-type questions.

From Figure 1, only a few students drew all the lone pairs of electrons required, expanded bonds/atoms, redrew or provided the correct starting material, and showed mapping of atoms. Unfortunately, the reaction mechanism-type questions had the most errors. The major causes of low scores and errors of students on these questions were not drawing resonance structures, not expanding atoms/bonds, and mapping of the atoms in the reaction mechanism. Among these major causes of low scores and errors, not drawing resonance structures contributed the most to students' low scores. A significant proportion of the students (87.5 %) did not draw resonance structures where necessary in their reaction mechanism, even though they had been taught how to draw resonance structures (Figure 1). The effect of not drawing these structures was that most of the students drew incorrect products. For question 2a (Appendix 1) which required students to predict the major product and show a mechanism for its formation, most students did not draw the resonance structure and hence drew the wrong product. Figure 2 shows a comparison of a student's responses to question 2a to the expected answer.

As shown in Figure 2, Esi drew a product containing an alcohol functional group from protonating the intermediate containing alcohol instead of drawing resonance structures from their protonation to continue the reaction (Figure 2). Expanding and mapping strategies have also been correlated with successful problem-solving in organic synthesis (Bod'e and Flynn, 2016). A study conducted by Flynn and Featherstone (2017) on students' successes, strategies, and common errors in answering questions involving electron-pushing (curved arrow) formalism revealed that not expanding or mapping of atoms and electrons was a major source of students' errors. In this study, a higher percentage of students (>50%) did not expand atoms or bonds where necessary (Figure 1). Figure 3 presents a comparison of students' responses to question 2b to the expected answer.

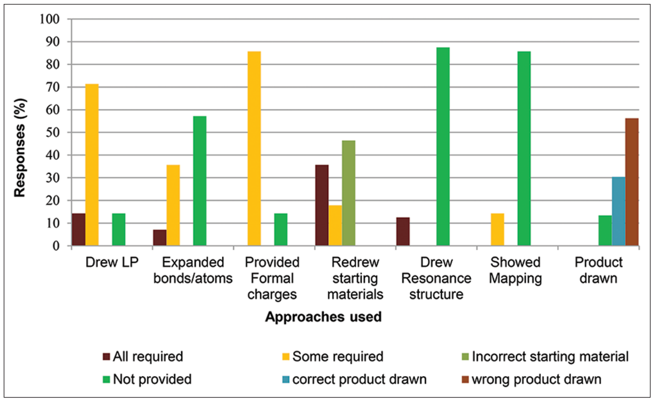
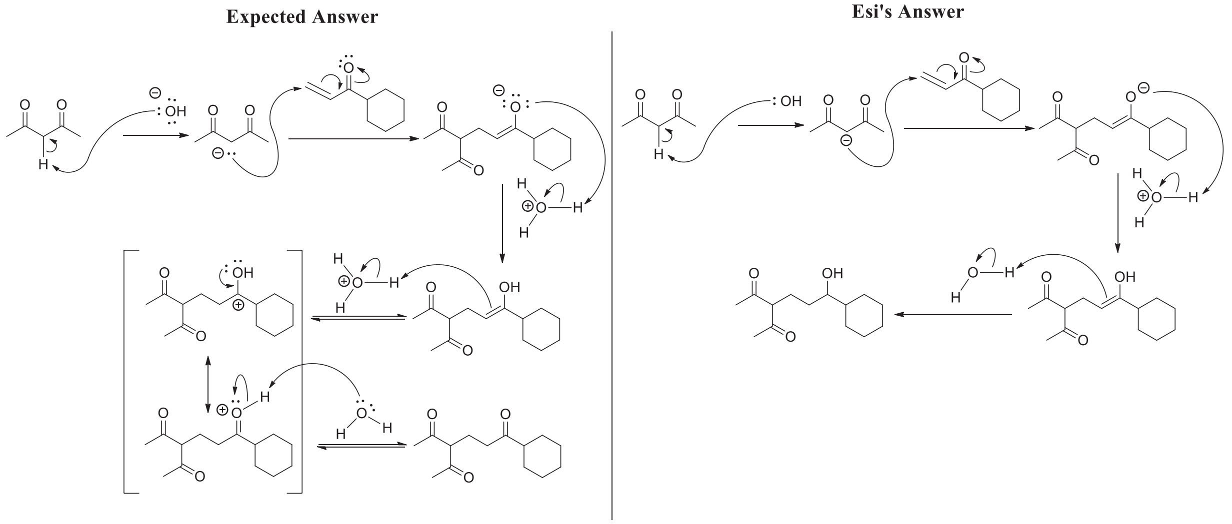


Figure 1: Approaches utilized by students in their responses to the reaction mechanism-type questions

For question 2b as illustrated in Figure 3, the majority of the students did not draw the resonance structure for the Wittig reagent at the initial stages of their reaction mechanism (Figure 3). Neither did these students expand the molecular structure of the intermediate after the reaction between the Wittig reagent and the ketone. Consequently, these students could not provide the oxaphosphetane intermediate and therefore provided the wrong product. Furthermore, a chunk of the students (85.7%) did not show any mapping of the atoms in the compounds involved despite the crucial role it plays in guiding the generation of starting materials/chemical equivalence in synthetic designs (Figure 1).

The findings from this study also indicated that nearly 70% of the students did not provide the product or drew the wrong product (Figure 1). Students' difficulty with providing or drawing the correct final product could be attributed to their inability to draw resonance structures, expand atoms/bonds, and mapping of atoms in the compounds. Even students who drew the resonance structures and expanded atoms but did not show evidence of mapping of atoms had issues with the number of carbon chains in the final product. This finding corroborates that of Bodner and Domin (2000) that the correct utilization of problem-solving strategies, such as mapping atoms, generates information or insight that leads to the correct answer, whereas incorrect use of the strategy makes it difficult or impossible to obtain the correct answer. Another cause of students' inability to draw the correct final product was that some students redrew the starting material or intermediate in an orientation that made it difficult for them to draw the correct product. Moreover, only a few students drew all the lone pairs required in every step of their reaction mechanism (Figure 1). Meanwhile, a large number of students left out some lone pairs. In some cases, students drew only the lone pair they needed for arrow pushing (Figure 2). In addition, a small number of students (9 %) did not draw lone pairs in their reaction mechanism but instead drew arrows from formal charges (Figure 2). Sunasee (2020) observed that students struggle with proposing electron-pushing mechanisms including errors related to formal charges, rearrangement, and arrows.

Another possible source of error was the use of arrow pushing in the reaction mechanism. It is extremely important for an organic chemist to understand reaction mechanisms, which entail EPF, to be able to solve synthetic problems (Bhattacharyya, 2014). How well a student draws these curved arrows is highly indicative of their success in solving synthesis problems (Ferguson and Bodner, 2008). To this end, students' use of arrow-pushing formalism was analyzed. Figure 4 shows students' use of arrows in the reaction mechanism-type questions.

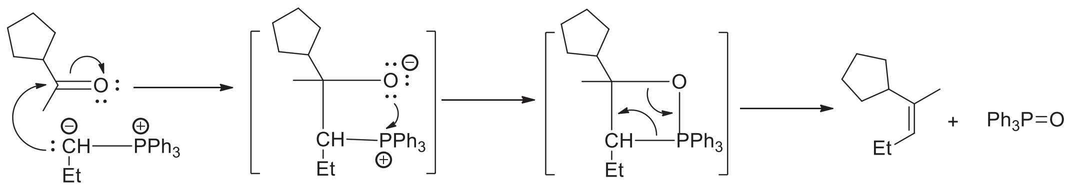


Expected Answer

Esi's Answer

Figure 2: Comparison of a student's responses to question 2a to the expected answer

Expected answer



Common answer provided by students

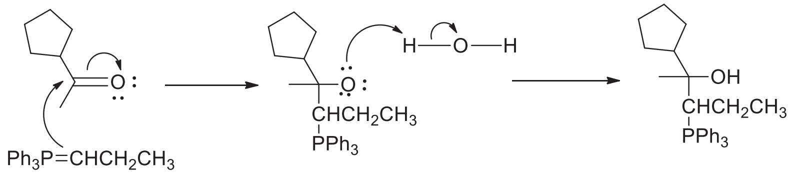


Figure 3: Comparison of students' responses to question 2b to the expected answer

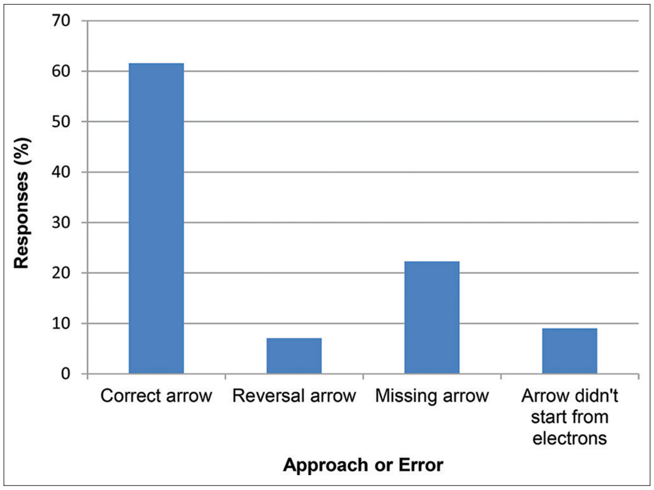


Figure 4: Students' use of arrows in the reaction mechanism-type questions

Analysis of students' use of the arrow-pushing strategy revealed that a more significant number of the students (>60%) used the correct arrow-pushing in tracking electron movement in the reaction mechanism (Figure 4). However, there were a few incidences of missing arrows, reversal arrows (i.e., arrows starting from atoms instead of electrons), and arrows that did not start from electrons (arrows from formal charges instead of electrons). Notably, arrows emanating from formal charges and atoms were deemed errors in this study because charges are not involved in forming bonds, but electrons are. The assertion, as mentioned, is in line with that of Carle et al. (2020), who reported that electrons, not atoms or charges, form bonds. Hence, curved EPF arrows should begin at electrons. The results show that the majority of the students (61.6%) understood bonding changes in the reaction.

Students' Approaches and Errors in Proposing the Synthesis-Type Problems

Figure 5 shows approaches used by students in responding to propose the synthesis-type questions.

Analysis of students' responses revealed that all students attempted to use retrosynthesis to solve these questions. A significant number (40.2%) of students chose a good bond disconnection in all cases. In comparison, the rest (59.8%) provided the appropriate bond disconnection in most cases (Figure 5). The results suggest that students have grasped the concept of the disconnection approach and can identify the various types of bonds to disconnect where necessary. Another reason could be that students were familiar with the reactions needed to accomplish the synthesis of the target molecules. The aforementioned observation is consistent with Flynn (2014) who reported that students' familiarity with the reactions leads to successful determination of how a bond is formed. Unfortunately, most of the students (58 %) could not generate the correct starting or the synthetic equivalent even though they made the right disconnections. According to Flynn (2014), some students who can identify the necessary reaction to generate a particular bond may find drawing the actual starting materials for the synthesis difficult. The inability of students to generate correct starting material/chemical equivalence after disconnection was a major cause of low scores in the proposed synthesis-type questions. These difficulties show how important it is to implement targeted interventions and instruction strategies to help students develop the necessary skills in generating a starting material or a synthetic intermediate.

Another reason for students' inability to generate correct starting material/synthetic intermediate could be because the majority (nearly 80%) of the students did not show the mapping of atoms as a strategy in their responses (Figure 5). Further analysis of students' responses to the synthesis of the target molecule based on the Witting reaction revealed that the majority of the students were confused about which portion from their disconnection could function as the nucleophile (the Wittig reagent) or the electrophile (aldehyde). Figure 6 shows a comparison of the expected retrosynthesis to the common retrosynthesis provided by students to question 3a.

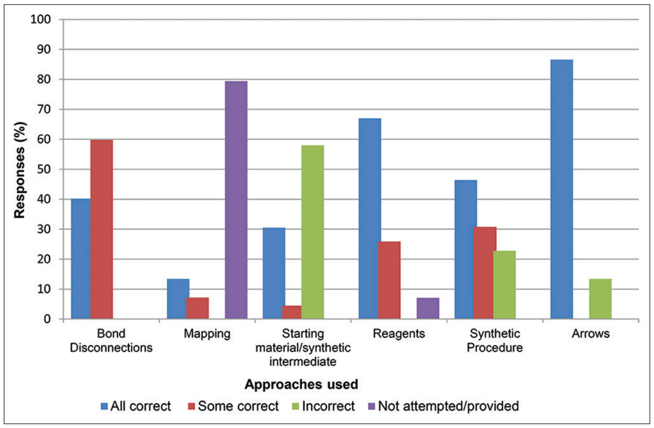
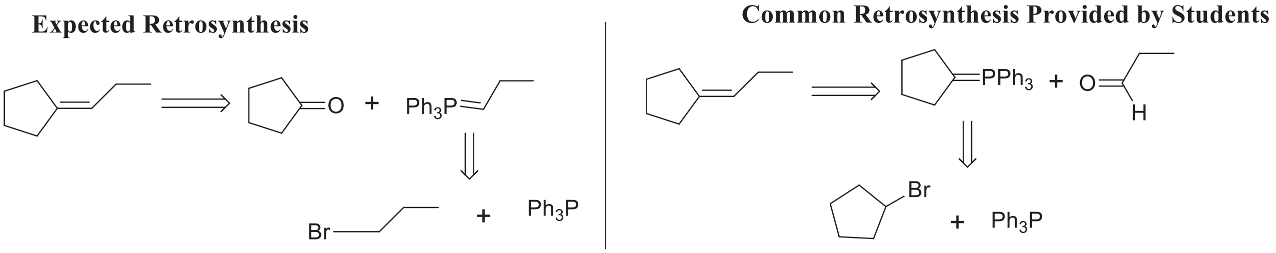


Figure 5: Approaches used in responding to propose the synthesis-type questions

A significant number of the students selected the starting material, which may involve competition of SN2 with E2 reaction during the preparation of the Wittig reagent and give a low yield of the target molecule (Figure 6). Even students who identified the right partners had challenges with the number of carbon chains for their starting materials. However, a simple mapping of the atoms (numbering of the carbon atoms) could have been an effective strategy in obtaining the correct starting materials. Bodé and Flynn (2016) have reported that students who employed mapping of atoms and electrons between starting materials and products were successful in their synthesis.

Furthermore, most students supplied the appropriate reagents and provided the correct synthesis procedure required to obtain the target molecules even though they had provided the wrong starting materials. Only a few students missed some of the synthetic steps or some of the reagents. These observations suggest that students had some knowledge about the reactions required in proposing the synthesis of the target molecules. Unfortunately, as already mentioned, the knowledge of these reactions was insufficient to successfully solve synthesis-type questions. Therefore, it is important for instructors to focus on intervention strategies that will assist students to integrate their knowledge of chemical principles, reactions, and skills to propose the synthesis of a specific target molecule.

As observed under the reaction mechanism-types questions, students used the correct arrows when required. Similarly, students were able to use the correct arrow for a transform in their retrosynthetic analysis and also used the correct reaction arrow for the synthesis of the target molecule. Only a few students (<14%) continued the use of the transform arrow for the synthesis of the target molecule. The use of the arrows (a transform and reaction arrow) in propose the synthesis type was considered a relatively minor error and, therefore, did not attract any penalty in grading. In effect, the results imply that students understand which arrow to use in a given synthesis problem.


Expected Retrosynthesis

Common Retrosynthesis Provided by Students

Figure 6: Comparison of expected retrosynthesis to common retrosynthesis provided by students to question 3a

CONCLUSIONS

This study evaluated the approaches used by undergraduate Chemistry major students while concurrently unmasking the common errors that hindered their successful resolution of synthetic problems. The questions for this study were categorized into identifying a reaction and providing a reagent, and reaction mechanism, as well as proposing a synthesis of a target molecule. The findings from the analysis of the data revealed that although students obtained high scores in identifying reactions and providing reagents, they had low scores in answering questions on reaction mechanisms and proposing the synthesis of target molecules. The study's findings revealed that students' overreliance on memorization rather than on applying their knowledge in meaningful ways may have hampered their success in responding to synthesis problems.

Further analysis of the data set showed that the majority (>85%) of the students accurately identified various reactions and provided the requisite reagents to successfully complete the reaction. However, common errors of students in providing reagents for organic transformations basically related to missing reagents, incorrect reagents, and misplacing reagents when directed synthesis was needed. Examination of students' competency in drawing reaction mechanisms to obtain particular products revealed many errors. For instance, many students omitted lone pairs, failed to expand atoms/bonds, did not draw resonance structures, or could not draw the correct products from their reaction mechanisms. The analysis revealed that over half of the students employed correct arrow pushing to track electron movement. In contrast, a few students made errors, such as drawing reversal arrows or starting arrows from formal charges instead of electrons and missing arrows.

It is worth noting that all students in this study attempted to apply retrosynthesis analysis in proposing the synthesis-type questions. Over 40% of the students demonstrated a proficient selection of bond disconnection, whereas nearly 60% of students made correct bond disconnections in most cases indicating a good understanding of the approach. Again, students consistently demonstrated proficiency in selecting appropriate reagents in most cases. Despite making correct disconnections, most students struggled to generate the appropriate starting material or synthetic equivalents, which led to lower scores in these types of questions. The inability to generate these intermediates primarily stemmed from the fact that a significant majority (approximately 80%) of students did not employ an atom mapping strategy to guide them even though they had been taught atom mapping.

These errors mentioned earlier, and difficulties in solving synthesis-type questions indicate a need for instructional strategies that enhance understanding and problem-solving skills in organic synthesis. Educators should focus on teaching methods that encourage the application of reaction mechanisms and other strategies such as retrosynthesis analysis, atom mapping, etc, in synthesis design to improve students' ability to integrate knowledge and skills in organic chemistry.

Limitations

Many constraints apply to this study. A primary limitation of this study is that the data came from a single class at a single university; as such, the generalization of the conclusions is limited to the unique setting in which the study was carried out. Furthermore, the synthesis-type questions used in this study were condensation, oxidation and reduction, Wittig, and organometallic reactions, with expanded structures, target molecules, and starting materials where applicable. This simplification may cover only some areas students might encounter throughout their organic synthesis course. Still, it was implemented to minimize confusion and make it easier for students to answer the questions. Consequently, other facets of common difficulties, approaches, and errors in organic synthesis may still be hidden.

Implication for Research and Practice

This study highlights students' strategies, common pitfalls, and errors that hinder students' success in organic synthesis. Based on the study's findings, it is recommended that instructors should focus on teaching strategies that promote understanding and application of reaction mechanisms in synthesis design. Consequently, future research could explore different teaching strategies, including inquiry-based learning, collaborative problem-solving, and the use of technology to enhance students' understanding of reaction mechanisms and improve problem-solving skills in organic synthesis. Educators should also prioritize strategies (such as mapping of atoms, drawing of resonance structures, expanding bonds/atoms, generation of starting materials, etc.) that help students generate starting materials and provide correct products during organic synthesis design. Furthermore, instructors should make an effort to create an enabling learning environment in the classroom with ample opportunities like hands-on practice and real-world applications of organic synthesis to enable students to apply their knowledge and skills to different synthesis problems. Instructors should take great pleasure in helping students develop problem-solving skills along with giving students the confidence to take on difficult synthesis problems.

The findings of this study also revealed that many students rely on rote memorization rather than a conceptual understanding of organic synthesis. Therefore, future research could investigate assessment tools that evaluate not only students' final written responses but also their problem-solving processes. This could include formative assessments that help students explain their reasoning and strategy, giving the instructor a better idea of their level of understanding and areas for improvement. Finally, the current study was conducted in a single class at one university, which limits the generalizability of the findings. For future studies, a longitudinal approach could be used to track students' progress across several semesters or institutions. Such a study could provide a holistic understanding of how students develop problem-solving skills and how instructional interventions affect their learning outcomes over time.

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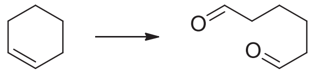
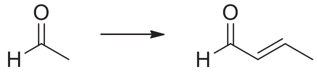
APPENDIX 1

1. Identify the following reactions, and provide the reagent(s) necessary to achieve the transformation.

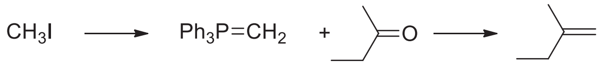
(a)



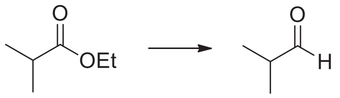
(b)



(c)

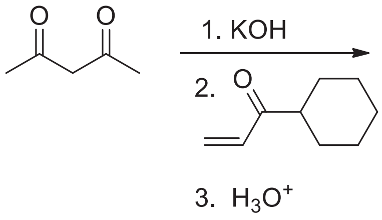


(d)

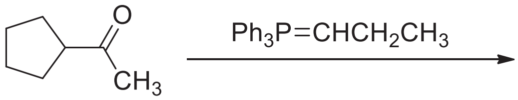


2. Predict the major product of the following and show a mechanism for their formation:

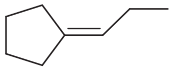
a)



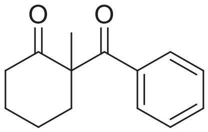
b)



3. (a) How would you synthesize the TM below using the Wittig Reaction?



(b) Starting with cyclohexanone, provide a synthesis for the target molecule below. It may help to first do a retrosynthesis of the TM.



APPENDIX 2

Appendix Table A1: Coding template used for the analysis of students' responses to the synthesis-type questions

Coding template for questions					
Reaction mechanism-type questions		**Propose synthesis-type questions**		**Identify reactions and provide reagent-type questions**	
Lone Pairs (LP)	All LP	Bond Disconnections (BD)	All BD R/W	Identify reaction	All reactions R/W
	Some LP		Some BD R/W		Some reactions R/W
	Not drawn		Not provided		Not attempted
Expanded bonds/ atoms	All required	Starting Materials/ Synthetic equivalent (SM)	All SM R/W	Provide Reagents	All reagents R/W
	Some required		Some SM R/W		Some reagents R/W
	Not provided		Not provided		Not provided
Mapping evidence	R/W	Mapping evidence	R/W		
Redrew starting materials or Synthetic equivalent (SM)	All SM R/W	Provided Reagents	All PR R/W		
	Some SM R/W		Some PR R/W		
	Not provided		Not provided		
Drew resonance structure (RS)	All RS R/W	Synthesis Procedure (SP)	All SP R/W		
	Some RS R/W		Some SP R/W		
	Not provided		Not provided		
Formal Charges (FC)	All FC R/W	Use of Arrows	All arrows R/W		
	Some FC R/W		Some arrows R/W		
	Not drawn		Not attempted		
Use of Arrows	Reversal arrows				
	missing arrows				
	Did not start from electrons				
	Correct arrows				
Provided the Product	R/W				