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Assessing conceptual difficulties experienced by pre-service chemistry teachers in organic chemistry

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Abstract

Organic chemistry is a mandatory component of chemistry II and chemistry III within the curriculum for pre-service chemistry teachers (PSCTs) pursuing a degree in chemistry teaching. The organic chemistry course sequence is well recognized as challenging and unapproachable for students, despite its significant relevance and impact across several sectors. While efforts have been made to recognize and deal with challenges faced by students in the cognitive and psychomotor aspects, there has been less attention given to identifying PSCTs' conceptual difficulties and misconceptions of organic chemistry. This includes the subsequent strategies to design instructions to enhance students' learning experiences, which are crucial elements in addressing their achievements in organic chemistry. The study aimed to identify the conceptual difficulties and misconceptions encountered by PSCTs in organohalides and stereochemistry. Furthermore, the study aimed to suggest strategies to enhance PSCTs' understanding of the course. The study was situated within the theoretical framework of constructivism and employed an interpretivist qualitative case study design. The population under study consisted of all individuals who were enrolled in the Bachelor of Education program within the faculty of educational sciences. A cohort of 33 whole-class PSCTs who had registered for the chemistry III course, where organohalides and stereochemistry were taught as units, were purposefully selected to participate in the study. The main instruments were document analysis, formal written tests, and interviews. Data were analyzed using thematic analysis. The study revealed that PSCTs encountered difficulties when attempting to solve problems related to organohalides and stereochemistry. In addition, PSCTs had misconceptions about these concepts. The study, therefore, recommends the implementation of suitable and appropriate instructional strategies to enhance PSCTs' conceptual understanding and reduce misconceptions.

Keywords: chemistry, conceptual difficulties, misconceptions, organohalides, pre-service chemistry teachers, stereochemistry

INTRODUCTION

Chemistry is a scientific discipline concerned with the analysis and manipulation of the constituent chemicals that comprise matter. A branch of chemistry is organic chemistry that deals specifically with the study of molecules primarily consisting of carbon atoms. Organic chemistry necessitates individuals who possess the capacity to comprehend its principles both at the macroscopic and sub-microscopic scales, as well as the ability to establish connections between the symbolic representations employed at each level. According to Hanson (2017), possessing a comprehensive knowledge of the subject is deemed essential for careers and the pursuit of further studies. Consequently, such understanding serves as a fundamental element in the advancement of novel products within society.

At the institution, where this study was carried out, organic chemistry is included in the curriculum throughout the second and third years of the four-year undergraduate degree program for teacher trainees. In the second year of study, the curriculum includes a comprehensive module on chemistry II, which spans a whole academic year. Within this module, the sixth and

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Contribution to the literature

- This study offers suggestions derived from scholarly research about the conceptual difficulties associated with the spatial representation of stereochemistry, mechanistic reactions and assigning configurations of organic compounds.
- The study makes a significant contribution to the existing body of scientific literature, as it addresses a research gap in the exploration of PSCTs' conceptual and procedural knowledge about stereochemistry and organohalides in the context of Africa.
- Previous studies conducted in this region have not specifically explored this topic, therefore rendering the findings of this study novel and valuable.

seventh units are dedicated to organic chemistry. These units delve into several fundamental principles and concepts within organic chemistry. In the third year of study, pre-service chemistry teachers (PSCTs) are instructed on the topics of organohalides and stereochemistry as distinct components of the chemistry III curriculum. The successful continuation of learning the subject matter in these units necessitates PSCTs' possession of both conceptual and procedural knowledge.

The acquisition of conceptual knowledge and the attainment of meaningful learning in organic chemistry is contingent upon PSCTs' aptitude to acquire, establish connections, and discern distinctions between the microscopic, macroscopic, and symbolic dimensions (Johnstone, 1991). Comprehending the characteristics of matter across three distinct levels is a pivotal aspect in cultivating mental comprehension and achieving proficiency in organic chemistry. Nevertheless, the author has seen with apprehension that PSCTs frequently encounter difficulties when attempting to utilize their conceptual and procedural knowledge to solve problems related to organohalides and stereochemistry, even after receiving explicit instructions.

The literature review has substantiated that this observation is indeed accurate. According to existing literature, organic chemistry is widely recognized as a challenging discipline within the field of chemistry, posing significant obstacles for students (Asmussen et al., 2023; O'Dwyer & Childs, 2017), particularly those lacking prior knowledge in the subject matter.

Based on the findings of Anim-Eduful and Adu-Gyamfi (2022a) that students tend to see organic chemistry as a complex and challenging discipline, characterized by its abstract nature and the need for extensive memorization, students often have difficulties in comprehending and mastering this concept (Ayalew, 2015). This highlights the necessity of immediate interventions (O'Dwyer & Childs, 2017) to improve students' understanding.

In recent years, there has been a noticeable inclination toward research in chemistry education, with a specific focus on organic chemistry due to the identification of student difficulties and misconceptions, and the underlying causes of these challenges (Anim-Eduful & Adu-Gyamfi, 2022b; Ayalew, 2015; Salame & Khalil, 2023).

Teachers' understanding of the challenges faced by their students and the origins of these challenges is a significant component of pedagogical content information to guarantee the provision of high-quality teaching and learning experiences. Nevertheless, there is a scarcity of research undertaken in South Africa about the conceptual difficulties experienced by PSCTs in organohalides and stereochemistry.

Furthermore, Asmussen et al. (2023) and Keller and Hermanns (2023) have made recommendations to enhance students' conceptual understanding of organic chemistry. However, the vast range of conceptual problems makes it challenging to find strategies to meet students' needs.

The identification of areas of concept difficulty contributes to the provision of quality teaching and the effective implementation of educational reforms in the South African educational system. This study is therefore particularly relevant to educators, authors of educational materials, teacher training programs, and the broader field of teaching.

The present study endeavored to identify PSCTs' conceptual difficulties in understanding mechanistic reactions of organohalides and stereochemistry following instructions. Additionally, the study aimed to identify PSCTs' misconceptions of these concepts and further identify the assistance they require from their lecturers in enhancing their conceptual understanding.

Therefore, this study is designed to seek answers to the following questions:

1. What are the conceptual difficulties experienced by PSCTs on stereochemistry and mechanistic reactions of organohalides?
2. What misconceptions do PSCTs have about stereochemistry and mechanistic reactions in organohalides?
3. What strategies may be employed to augment PSCTs' conceptual understanding of stereochemistry and mechanistic reactions in organohalides?

LITERATURE REVIEW

Students' Difficulties with Organic Chemistry Concepts

Conceptual knowledge and procedural knowledge are key constituents of scientific pedagogy and acquisition. The term "conceptual knowledge" pertains to the comprehension of fundamental concepts and principles within a certain field. On the other hand, "procedural knowledge" refers to the capacity to execute specific methods or algorithms to address issues (Hiebert, 2013). There is a connection between conceptual and procedural knowledge, but the precise nature of this connection remains a subject of ongoing scholarly discourse. One perspective posits that procedural knowledge serves as the foundation for conceptual knowledge, whilst another viewpoint suggests that the relationship between the two is bidirectional (Blöte et al., 2001).

Concept difficulty refers to the degree to which a student can grasp an idea or issue (Oladejo et al., 2023). A considerable body of research has demonstrated that chemistry is a discipline that places significant cognitive demands on learners (Zoller & Tsaparlis, 1997). In "the nature of the chemical concept", Taber (2019) carries out a comprehensive analysis of the intricate nature of chemistry while Johnstone (1991) believes that the acquisition of knowledge in chemistry necessitates the ability to transition between several modes of representation, including symbolic, macroscopic, and sub-microscopic levels.

Organic chemistry is widely recognized as a challenging subject for learners (Anim-Eduful & Adu-Gyamfi, 2022b; Ayalew, 2015; Cartrette & Mayo, 2011), primarily due to its teaching methodology. Popova and Bretz (2018) examined students' comprehension of leaving groups and found that their knowledge structures were fragmented. A similar study conducted by Cartrette and Mayo (2011) revealed that there was a lack of understanding of organic chemistry-related concepts in students' mental models, leading to a tendency to use concepts interchangeably while engaging in problem-solving activities.

Anzovino and Bretz (2015) concur by similarly demonstrating student difficulties and strong correlations across concepts. For instance, students had difficulties differentiating between electrophilicity and nucleophilicity (Anzovino & Bretz, 2015). Furthermore, students also had difficulties in comprehending these chemical concepts indicated by inaccurate or incomplete definitions, and difficulty in determining the appropriate application of these concepts in a given problem-solving activity (Anzovino & Bretz, 2015; Xue & Stains, 2020). Anzovino and Bretz (2015), Popova and Bretz (2018), and Xue and Stains (2020) have identified factors contributing to these difficulties that include inadequate instructional strategies, reliance on rote memorization, and insufficient knowledge.

Misconceptions in Organic Chemistry

Studies of students' conceptions in the field of chemistry are grounded in the constructivist approach to learning, which underscores the notion that students actively develop their cognitive structures (Windschitl & André, 1998) by drawing upon their personal beliefs, attitudes, talents, and experiences both before, during, and after receiving instruction. Consequently, there may be disparities between the ways students perceive and understand chemistry concepts including misconceptions, alternative conceptions, naive beliefs, erroneous ideas, and personal models of reality (Prodjosantoso et al., 2019). This study used the term ''misconceptions'' for as researchers refer to it more often. A misconception may be defined as a cognitive construct, belief system, or perceptual framework that diverges from empirical reality and lacks a solid grounding in scientific reasoning (Luxford & Bretz, 2014).

Several studies have documented the presence of student misconceptions in organic chemistry (Anderson & Bodner, 2008; Widarti et al., 2017) as many of them deviate greatly from the scientifically recognized viewpoint and are subjectively based only on sensory input (Gilmore et al., 2017). For instance, McClary and Bretz (2012) provide the results of a study done at an American institution showing students' misconceptions while trying to classify organic molecules as basic or acid.

Previous studies have also investigated the misconceptions experienced by undergraduate students in learning organic chemistry concepts (Alsfouk, 2022; Anim-Eduful & Adu-Gyamfi, 2022b; Durmaz, 2018). However, the occurrence of misconceptions, specifically about the concept of organohalides and stereochemistry, is relatively scarce.

It is, therefore, appropriate to explore PSCTs' misconceptions in organic chemistry concepts such as organohalides and stereochemistry in order to design instructions to reduce student misconceptions. Durmaz (2018) carried out an investigation to analyze the cognitive structures and misconceptions held by prospective chemistry teachers in stereochemistry. The study revealed that the participants had misconceptions about stereochemistry even though they were pursuing a career in chemistry education.

Misconceptions, which often contradict scientific notions, may arise from textbooks, prior knowledge, and erroneous understanding (Kose, 2008; Kumi et al., 2013). To tackle these misconceptions, Silva et al. (2019) employed a board game to actively include students in the teaching-learning process.

THEORETICAL FRAMEWORK

Vygotsky's constructivist theory places significant emphasis on the influence of social interaction and cultural environment in the process of knowledge acquisition and comprehension (Palincsar, 1998). Vygotsky posits that the acquisition of knowledge is a social phenomenon, wherein individuals engage in cooperative endeavors and interpersonal exchanges to facilitate learning. The use of the constructivism theory in the realm of organic chemistry education has the potential to effectively mitigate conceptual difficulties and misconceptions. Galloway and Bretz (2015) advocate for the use of constructivism as a pedagogical approach inside the laboratory environment. According to their argument, the process of meaningful learning, a fundamental component of the constructivist approach, encompasses the amalgamation of cognitive processes, emotional responses, and behavioral actions. Through the implementation of laboratory experiences that foster meaningful learning, students can actively create their understanding of ideas related to organic chemistry.

The constructivism theory provided direction in this study to understand how students create personally meaningful understandings during classroom instruction. The use of constructivist teaching approaches necessitates teachers, as a primary step, to acknowledge the misconceptions held by their students. Subsequently, these alternative conceptions must be considered while encouraging students to actively engage in the learning process through activities such as group discussions, problem-solving sessions, and hands-on experiments (York & Orgill, 2020). This approach also promotes a deeper understanding of concepts by allowing students to apply their knowledge in real-world contexts and actively participate in their learning (Berisha, 2020). By actively engaging with the material, students are more likely to retain information and develop critical thinking skills (Smith et al., 2005).

METHODOLOGY

This study employed the interpretivist qualitative case study methodology to explore organic chemistry learned by third-year PSCTs and offer detailed descriptions of the identified PSCTs' conceptual difficulties and misconceptions. Furthermore, the study was heuristic as it provided valuable insights into how PSCTs articulated their explanations of various events, while also identifying potential causes that were logically consistent with their conceptual knowledge of the concept under study. Also, the characteristics of the research inquiries, the absence of any controlled intervention, the intended outcome, and the focal point of the inquiry guaranteed that a case study effectively achieved the objectives of this study (Yin, 2018).

The author taught organic chemistry to third-year Bachelor of Education degree students who registered for chemistry III at a university in the Eastern Cape Province of South Africa in 2023. This module is a year-long course. These PSCTs are majoring in physical sciences and mathematics. Organic chemistry was taught as a unit during the first semester using lecture methods and video lessons. In the first block of semester 1, organohalides and stereochemistry were discussed. The main objective for these two sub-units was to provide PSCTs with advanced knowledge of the structures, properties, and mechanistic principles underlying reactions, specifically nucleophilic substitution, and elimination reactions. The units further presented the concept of stereochemistry, encompassing enantiomers, diastereomers, meso compounds, and stereoisomerism, with a concise overview of configurational and conformational isomerism, and placed emphasis on the significance of stereochemistry in chemical processes.

The study employed convenience sampling to select the entire class to take part in the study, for the reason that the author is the instructor of the module and has ease of access to the students. The participants consisted of 33 PSCTs (10 females and 23 males), with an average age of 21.

Instrumentation

The main instruments employed in this study were document analysis of course outline, a formal written test and interviews. To ascertain the specific areas in which PSCTs encountered difficulties, as well as to address the primary research questions, the study selected conceptual and procedural knowledge assertions that were essential for PSCTs to acquire a comprehensive understanding of organic chemistry, specifically focusing on organohalides and stereochemistry. A thorough analysis was conducted of many general chemistry textbooks to identify pertinent conceptual and procedural knowledge about the discussed concepts. The knowledge assertions in the eight conceptual categories, as provided in **Table 1**, were formulated based on this information, supplemented by inputs from colleagues.

Table 1. Conceptual & procedural knowledge assertions on organohalides & stereochemistry (McMurry, 2010)

1	Chirality
a	Chirality refers to the property of molecules that are mirror images of one other and cannot be superimposed. Describing a molecule as chiral implies that its mirror image, which it must possess, is distinct from itself.
b	Determination of a molecule's chirality or achirality: Asymmetrically substituted carbon atom, carbon atom that forms bonds with four distinct atoms or groups.

Table 1 (Continued). Conceptual & procedural knowledge assertions on organohalides & stereochemistry (McMurry, 2010)

2	Rules for specifying configuration sequences
a	The nomenclature of “right hand” and “left hand” is employed to designate the enantiomers of a chiral molecule. The stereocenters are designated as either R or S.
b	Rule 1: Four atoms immediately connected to the chirality center should be examined and ranked based on their atomic numbers. The atom possessing the greatest atomic number is assigned the highest position (first), while the element with the lowest atomic number (often hydrogen) is assigned the lowest position (fourth)
c	Rule 2: If initial atoms cannot be ranked to make a judgement, then examine 2nd, 3rd, & 4th atoms away from point of distinction.
d	According to rule 3, atoms bonded to multiple bonds can be considered comparable to an equal number of atoms bonded with single bonds. In assigning priority, position molecule with lowest priority directed away from observer.
e	When a curved arrow is depicted from substituents ranked highest to 2nd highest to 3rd highest (1, 2, & 3), & it follows a clockwise direction, configuration of chirality center is referred to as R (derived from Latin term “rectus” meaning “right”).
f	If an arrow originating from points 1, 2, and 3 exhibits an anticlockwise direction, it indicates that the chirality center possesses the S configuration, derived from the Latin term “sinister”, which denotes “left.”
g	Diastereomers often exhibit significant variations in their physical characteristics, while enantiomers have indistinguishable qualities except for their ability to rotate the plane of polarized light in opposite directions.
3	Meso compounds refer to a class of chemicals that possess chirality centers while being achiral.
4	A brief review of isomerism
5	Mechanistic reactions of organohalide
a	Organohalides are a category of compounds characterized by the presence of one or more halogen atoms attached to a sp3 orbital of an alkyl group.
b	The order of carbon-halogen bond lengths and bond dipole moments is, as follows: C-F < C-Cl < C-Br < C- This phenomenon can be ascribed to the disparity in electronegativity between carbon and the halogen atom. A higher electronegativity differential leads to increased bond polarity, resulting in a bigger dipole moment.
c	When assigning names to organohalides by IUPAC, identify the longest carbon chain. The carbons of the parent chain should be numbered starting from the end that is closer to the first substituent. The alkyl groups are regarded as alkanes that have undergone substitution with a halogen.
d	Alkyl halides exhibit three distinct levels of substitution, namely, primary (1°), secondary (2°), and tertiary (3°).
6	Preparation of alkyl halides
a	The most often employed approach to synthesizing alkyl halides involves the conversion of alcohols, which may be readily derived from carbonyl compounds.
7	Reactions of alkyl halides
a	Alkyl halides, denoted as RX, undergo a reaction with magnesium metal in the presence of an ether solvent, resulting in the formation of alkyl magnesium halides, represented as RMgX (Grignard reagents).
b	The halogen atom can depart alongside its bonded pair of electrons, resulting in the formation of a halide ion. This ion is considered stable, and hence halides are recognized as proficient leaving groups.
8	Mechanisms of SN1 and SN2
a	The nucleophile Nuc:$^-$ initiates the displacement of the leaving group (resulting in X$^-$) from the carbon atom by the utilization of its lone pair to establish a novel bond with the carbon atom. The nucleophile Nuc:$^-$ undergoes a substitution reaction with the leaving group, resulting in the formation of X$^-$. This substitution occurs as the lone pair of Nuc:$^-$ forms a new bond with the carbon atom.
b	Term SN1 refers to a kind of reaction known as unimolecular nucleophilic substitution. Process consists of two distinct stages. Step 1 involves ionization of alkyl halide, resulting in the formation of a planar carbonium ion. The planarity of the carbonium ion can be attributed to the sp^2 hybridization of the carbon atom, resulting in a positive charge.
c	Step 2: The nucleophile can initiate an assault on the planar carbonium ion from either the left or right side, resulting in the formation of the desired product. The rate-determining phase in this process is ionization, as it is the stage with the slowest rate.
d	The SN1 reaction exhibits first-order kinetics, therefore earning its designation as an SN1 reaction.
e	The order of reactivity: Benzyl halide > allyl halide > tertiary halide > secondary halide > primary halide > methyl halide. It is important to note that if an alkyl halide has optical activity, SN1 reactions will result in racemization.
f	Electrophilic nature of carbon atom may be attributed to its bonding with a halogen, which is more electronegative. This results in withdrawal of electron density from carbon atom, leading to polarization of carbon halogen bond. Consequently, carbon atom acquires a partial positive charge, while halogen atom carries a partial negative charge.
g	The nucleophile is drawn towards the electrophile due to the presence of electrostatic charges. The nucleophile engages in an attack on the electrophilic carbon using electron donation involving a pair of electrons.

Table 1 (Continued). Conceptual & procedural knowledge assertions on organohalides & stereochemistry (McMurry, 2010)

8	Mechanisms of SN1 and SN2
h	The halogen atom serves as the leaving group when it dissociates from the carbon atom, taking with it the pair of electrons that were previously shared between the two atoms.
i	The reactivity order of alkyl halides exhibits variation in the following manner: 1°halide > 2°halide > 3° halide. The reactivity order of primary alkyl halides is as follows: CH3X < C2H5X < C3H7X. It is important to note that if an alkyl halide has optical activity, SN2 reactions result in Walden inversion.
j	The reaction is commonly described as coordinated, occurring in a singular step when formation of a new bond coincides with breaking of the existing link. The transition state is a state characterized by the maximum energy level, as opposed to being an intermediate stage. Bimolecular reactions often exhibit second-order overall rate equations.
k	The pace and mechanism exhibit consistency since the method necessitates a collision between the hydroxide ion and methyl iodide. Both species coexist in the transition state, and the rate of collisions is directly proportional to the concentrations of the reactants.
l	In process of eliminating HX from an alkyl halide, alkene product that is more strongly substituted tends to be predominant outcome. There are 3 often observed processes in organic chemistry, namely, E1, E2, & E1cB reactions.

The statements underwent a thorough review process with three colleagues. The reviewers' remarks, together with further inputs from colleagues, were utilized to revise the initial set of statements. The information presented encompassed three key components:

(a) a collection of scientifically precise information to enable comparison of PSCTs' responses with scientifically accurate perspectives;

(b) a thorough and all-encompassing inventory of the knowledge necessary for PSCTs to understand organohalides and stereochemistry; and

(c) the foundation for constructing the interview protocol and procedures for data analysis.

The interviews and the formal written test questions were derived from a compilation of conceptual and procedural statements to explore the understanding of PSCTs on organohalides and stereochemistry, as well as to identify any conceptual difficulties and misconceptions they may have encountered. Nevertheless, due to the quantity and comprehensiveness of the assertions, it was determined that questioning each component or facet of the statements would not be pursued. Instead, a somewhat broad inquiry was made into each statement.

The test questions consisted of two distinct components: part A centered on the biographical profiles of PSCTs, and part B was based on the data provided in **Table 1**. 18 test questions, based on the knowledge assertions in the eight conceptual categories in **Table 1**, were formulated. The questions underwent a thorough review by three colleagues. The reviewers' remarks, together with further input from colleagues, were utilized to revise the initial set of items in the test. The revised questions were administered to PSCTs as a formal test.

Data Collection Procedure

The individual written test was administered to PSCTs during chemistry III lectures. However, the test was not for grading purposes. Yet PSCTs were informed that the test was a mock test in preparation for their mid-semester examination. This ensured that PSCTs gave responses that accurately reflected their conceptual understanding and difficulties in organohalides and stereochemistry.

After PSCTs wrote the test, fifteen PSCTs were purposefully selected from the sample and were invited for 30 mins interviews to understand the reasons behind their conceptual difficulties and misconceptions and further corroborate their answers in the written test.

The study adhered to normal ethical considerations. All members of the class agreed to participate in the study voluntarily upon completion of the first block of instruction. The interviews were conducted with the participants' consent and recorded in audio format, while being accompanied by notetaking. The course material was utilized to formulate both conceptual claims and procedural assertions. For anonymity and confidentiality, PSCT responses were labelled as PSCT1, PSCT2 up to PSCT33. All the transcripts were sent to the participants for member checking.

Analyzes of Data

Analysis of the qualitative data involved document (test scripts) analysis and thematic analysis of the interview data to identify patterns, trends, and relationships. First, the course syllabus was scrutinized for conceptual and procedural knowledge items, which were used to formulate the items in **Table 1**.

For the test items, the author marked all written responses, tallied scores, and identified PSCTs' difficulties and misconceptions. PSCTs' answers for each question were written on one sheet as summaries, which were then reviewed for common and dissimilar responses to identify PSCTs' conceptual difficulties and misconceptions. Three criteria were used to categorize PSCT difficulties and misconceptions: first, any written response, which showed PSCTs' lack of understanding was coded as "having conceptual difficulties"; second,

Table 2. Frequencies of PSCTs' responses on written tasks on organohalides

Question number	Percentage of PSCTs' conceptual & procedural knowledge (n)		
	Not understand	Understand	Have misconceptions
1	10	3	20
2	9	3	21
3	4	6	23
4	7	20	6
5	13	0	20
6	6	8	19
7	22	1	10
8	4	19	10
9	14	3	16

Table 3. Frequencies of PSCTs' responses on written tasks on stereochemistry

Question number	Percentage of PSCTs' conceptual & procedural knowledge (n)		
	Not understand	Understand	Have misconceptions
1	9	5	19
2	8	4	21
3	5	5	23
4	6	7	20
5	9	6	18
6	5	18	10
7	21	6	6
8	14	11	8
9	5	10	18
10	4	21	8

Figure 1. Predicting product of a substitution reaction (McMurry , 2010)

the response that was conceptually correct was coded as "understand"; and third, the written response shows an alternative response, which is not factual and is coded as a misconception. I also used Stroumpouli and Tsaparlis's (2022) way of framing errors and misconceptions. The recorded interviews were thematically analyzed (Braun & Clark, 2006) by listening to the audio repeatedly, which helped the author to identify emerging themes and patterns, which were further discussed in line with constructivist theory.

RESULTS

The frequencies of PSCTs' responses for both organohalides and stereochemistry are given in **Table 2** and **Table 3**. The results of the study are presented in line with the conceptual and procedural knowledge statements in **Table 1**. However, not all statements in **Table 1** are included in the results. The author selected only eight areas that PSCTs found most challenging, and with misconceptions, and included them for analysis.

PSCTs' Conceptual Difficulties on Organohalides

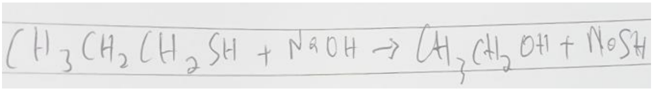
Conceptual knowledge and procedural knowledge are significant in the process of acquiring scientific information. According to the data shown in **Table 2**, few PSCTs (3 out of 33) exhibited conceptual and procedural knowledge with understanding regarding question 1, which pertained to providing the replacement product resulting from the reaction between 1-chloropropane and sodium hydroxide.

In this inquiry, participants were instructed to delineate the two reactants, while also discerning the nucleophile (namely, OH^-) and the leaving group (specifically, Cl^-). The correct equation is shown in **Figure 1**.

As illustrated in **Table 1**, the conceptual and procedural knowledge needed by PSCTs to solve this problem was to employ an approach to synthesize the alkyl halides with the base in predicting the alcohol. The result shows that few PSCTs managed to provide the correct product. This implies that PSCTs encountered conceptual difficulties in understanding organohalide reactions.

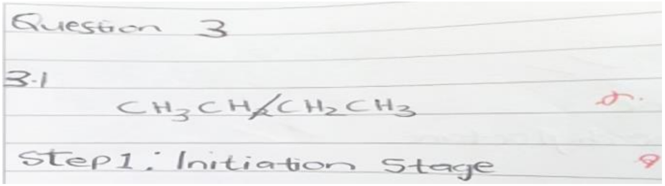
According to the data in **Table 2**, a significant number of PSCTs (10 out of 33) experienced conceptual difficulties when answering question 1. This shows that some PSCTs operated as the pre-action conception and could not provide a replacement product resulting from the reaction between 1-chloropropane and sodium hydroxide. This finding was evident during the interview. One PSCT lamented:

> "I experienced difficulties when I tried to write down the reaction products. I thought one of the products would be a metal or something, not even



$CH_3CH_2CH_2SH + NaOH \rightarrow CH_3CH_2OH + NaSH$

Figure 2. A conceptual difficulty exhibited by PSCT 12 (Source: Authors' own elaboration)



Question 3

3.1

CH_3CH_2/CH_2CH_3

Step1: Initiation Stage

Figure 3. A conceptual difficulty exhibited by PSCT 11 (Source: Authors' own elaboration)

> sure of myself. This reaction is too complicated" (PSCT14).

Question 2 pertains to the potential use of a substitution reaction within the context of synthesis by PSCTs. PSCTs were requested to explicate their approach to the synthesis of propane-1-thiol by a nucleophilic substitution process. In this question, the primary focus was on the identification of the specific group within the product that is introduced by the nucleophilic substitution. In this particular instance, the result comprises a -SH functional group, suggesting that it might be synthesized by the reaction between SH- and an organohalide (1-bromopropane), as illustrated stepwise in **Table 1**. However, the result shows that few PSCTs (three out of 33) solved this problem with understanding. However, **Table 2** also revealed that nine PSCTs (nine out of 33) showed a lack of understanding, resulting in their inability to respond. One PSCT gave the answer shown in **Figure 2**.

Figure 2 shows that PSCT12 experienced conceptual difficulties when solving this problem, which meant that the information was misconstrued. This finding suggests that PSCTs had a limited understanding of the synthesis of organohalides.

Question 3 was lengthy. PSCTs were asked to provide a detailed account of the stepwise process involved in the S_N2 reaction, accompanied by an illustrative representation involving specific reactants, as shown in **Table 1**. The study revealed that six PSCTs (six out of 33) demonstrated an understanding of the concept. These PSCTs correctly noted that the reaction occurs in a single step, where the incoming nucleophile approaches the leaving halide ion from 180 degrees away, resulting in a transition state with a partially formed C-OH bond and a partially broken C-Br bond. As the C-OH bond fully develops and the bromide ion and electron pair leave the C-Br bond, the stereochemistry at the carbon atom is flipped. But **Table 2** further reveals that four (four out of 33) PSCTs exhibited conceptual difficulties, resulting in their inability to provide the required information accurately. This was evident through instances when they either did not respond or misconstrued the underlying mechanistic reaction. Insufficient understanding of procedures and concepts, as well as inaccurate identification of reagents, can result in errors. PSCT11 provided response in **Figure 3**.

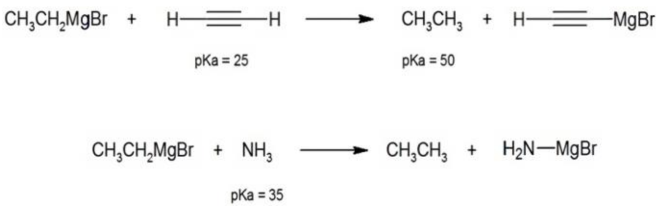


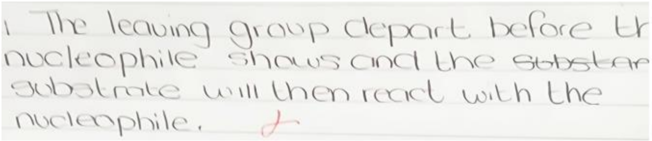
Figure 4. A stepwise reaction process (McMurry, 2010)

Question 4 necessitated the utilization of PSCTs to make informed predictions by elucidating the relative rates of the S_N2 reactions involving the OH- ion with 1-bromopentane and 2-bromopentane, as shown in **Table 1**. The majority of PSCTs provided accurate responses (20 out of 33). But they were unable to provide a rationale for their belief that 1-bromopentane would exhibit a higher rate of reaction. It was anticipated that PSCTs would assert that reaction rate of 1-bromopentane, a primary organohalide, would be higher than that of 2-bromopentane, a secondary organohalide, due to former being less sterically hindered.

Question 5 remained unanswered by most participants. The question provided a preamble about the traditional preparation of Grignard reagents by treating with an organohalide (normally organobromine) with magnesium metal as illustrated in **Table 1**. The question asked participants to assess the anticipated strength of ethyl Grignard as a base during its production, and thereafter provide a reasoned justification for the feasibility of the ensuing reactions within the synthesis process. **Figure 4** shows a stepwise reaction process. PSCTs encountered difficulties in providing a response to this question, resulting in a lack of responses. The limited number of participants who tried to address the question provided inaccurate answers, suggesting that they did not grasp the underlying concepts.

Question 6 requested participants to provide a detailed account of the step-by-step mechanistic process involved in S_N1 reaction between tert-butyl alcohol and HBr, resulting in formation of an organohalide molecule, as shown in **Table 1**. Eight PSCTs exhibited conceptual understanding and provided accurate solutions to the problem. PSCT19 narrated during the interview:

> "I know that the process comprises two distinct phases. The initial stage involves the reversible ionization of the organohalide compound in the presence of either an aqueous acetone or an aqueous ethyl alcohol solution. Then, uh ... hydroxyl group is initially subjected to protonation with the addition of hydrogen bromide (HBr). So, the protonated alcohol will



1 The leaving group depart before th
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Figure 5. A conceptual difficulty experienced by PSCT 33 (Source: Authors' own elaboration)

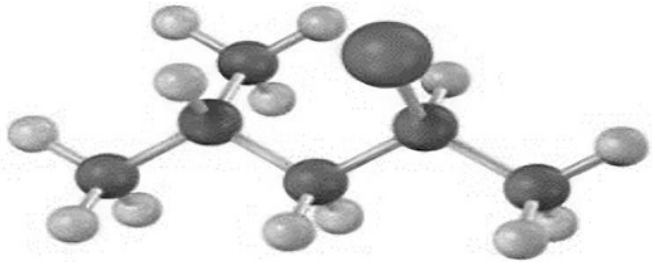


Figure 6. Predicting product of a substitution reaction (McMurry, 2010)

> undergo spontaneous dissociation, which is slow and rate-limiting. In the subsequent stage, the carbocation intermediate undergoes nucleophilic reaction, and this will result in the formation of the neutral substitution product."

Table 2 further revealed that 19 (out of 33) PSCTs exhibited conceptual difficulties, resulting in the provision of inaccurate information on the reaction. PSCT33 provided an inaccurate description of the process in the manner shown in **Figure 5**.

This explanation is deemed insufficient due to the lack of a qualitative description of the mechanism. This suggests that PSCT33 exhibited a limited understanding of the concepts and lacked the necessary conceptual knowledge to fully comprehend the material as it was presented. Few PSCTs indicated they understood the question however, they failed to explain it qualitatively. This was also evident during the interview when PSCTs could not give qualitative details of the reaction process.

Question 7 requested PSCTs to configure the molecule in **Figure 6** and illustrate the structure of the product in a nucleophilic substitution reaction with HS, which is characterized by a -Br.

The study revealed that the majority of PSCTs (22 out of 33) had conceptual difficulties in providing accurate responses to this question. One PSCT provided a response shown in **Figure 7**.

PSCTs were unsuccessful in assigning the configurations to both the substrate and the product.

PSCTs' Misconceptions on Organohalides

According to the data shown in **Table 2**, a significant number of PSCTs (20 out of 33) exhibited misconceptions regarding question 1, which pertained to providing the replacement product resulting from the reaction between 1-chloropropane and sodium hydroxide. Nevertheless, the study revealed that a significant number of PSCTs continued to hold the misconception that the interaction between an organohalide and sodium chloride would result in the formation of alcohol. There was also a misinterpretation regarding the specific sort of alcohol that would be produced and the nature of the secondary by-product that would be formed. An illustrative example of one PSCT 20 response is, as follows:

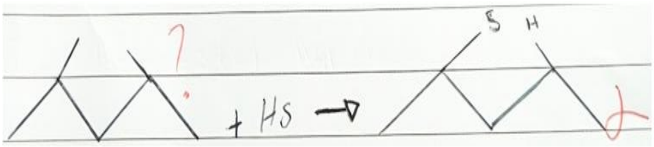
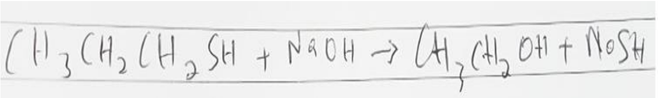


Figure 7. A conceptual difficulty experienced by PSCT 3 (Source: Authors' own elaboration)



$CH_3CH_2CH_2SH + NaOH \rightarrow CH_3CH_2OH + NaSH$

Figure 8. A conceptual difficulty experienced by PSCT 8 (Source: Authors' own elaboration)

> "If I substitute the NaOH into this haloalkane to produce alcohol, I will have to add water H_2O in this reaction" (PSCT20).

This result is a misconception. This misconception is prone to occur when PSCT lacks a comprehensive understanding of the conceptual and procedural knowledge that was presented to them.

Question 2 pertains to the potential use of a substitution reaction within the context of synthesis by PSCTs. The study revealed that out of the total number of PSCTs, 21 exhibited misconceptions pertaining to the subject at hand. PSCT8 gave the answers shown in **Figure 8**.

Figure 8 illustrates that PSCT8 had a misconception. This response and other similar responses by PSCTs indicated their misconceptions of substitution reactions. So, the information was misconstrued. This result suggests that PSCTs had a limited understanding of the synthesis of organohalides, with some misconceptions present.

In Question 3, PSCTs were requested to provide a detailed account of the stepwise process involved in the S_N2 reaction, accompanied by an illustrative representation involving specific reactants. The study revealed that a significant proportion of PSCTs exhibited misconceptions (23), resulting in their inability to provide the required factual scientific responses.

Question 6 requested participants to provide a detailed account of the step-by-step mechanistic process involved in the S_N1 reaction between tert-butyl alcohol and HBr, resulting in the formation of an organohalide molecule. The result shows that nine (nine out of 33) had misconceptions. PSCT16's response shows a misconception, and this was evident during the interview.

> "I think in the reaction, the leaving group will depart before the nucleophile arrives at the scene and the substrate will then react with the nucleophile, I guess."

This implies that PSCTs had misconceptions about step-wise SN1 mechanistic reaction of organohalides, which demonstrates a lack of comprehension and conceptual knowledge.

PSCTs' Conceptual Knowledge & Difficulties on Stereochemistry

According to the data shown in **Table 3**, five (out of 33) participants provided accurate responses by elucidating that the phenomenon of molecular handedness arises when a carbon atom forms bonds with four distinct atoms or groups, resulting in the loss of all symmetry, as explained conceptually on **Table 1**. The notion was elucidated by five participants who described it as stereoisomers that possess a mirrored image of one another. This was also evident in the responses provided by these students during the interview. One PSCT explained the phenomenon qualitatively with understanding:

> "Well, what I know is that molecules exhibiting chirality are characterized by their property of being non-superimposable mirror copies of one another. I can give you one instance of chiral items that are commonly encountered in everyday life, and that is the human hands. Our left and right hands exhibit a property known as chirality, wherein they possess mirror image symmetry but cannot be superimposed onto one another, just look at my hand (showing hand gestures)" (PSCT31).

According to the data shown in **Table 3**, a significant proportion of PSCTs (nine out of 33) provided information that indicated that they did not understand the question. One participant provided an inaccurate explanation by attributing it to the reactivity of molecules during the interviews:

> "It is a forming the same image on the mirror as the original one is called to be chiral" (PSCT 16).

This response shows a lack of understanding of the concepts taught and learned. This implies that the classification of a molecule as chiral was based on the presence of an atom with four distinct substituents. Their responses inferred a tetrahedral carbon atom with four distinct substituents, rather than perceiving the molecule as a whole entity.

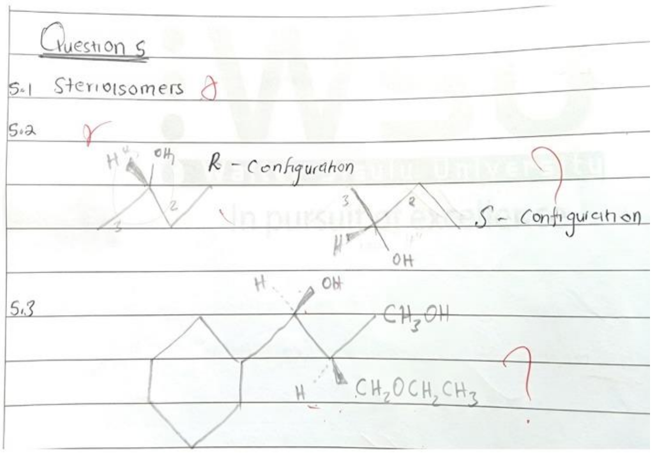


Figure 9. Conceptual difficulty experienced by PSCT 5 (Source: Authors' own elaboration)

Question 5 required PSCTs to assign the configuration (either R or S) to molecules with chirality centers in the given compounds. Nevertheless, prior to assigning the R and S names to a stereocenter, it is imperative for PSCTs to adhere to the principles they have acquired. According to the data obtained from the written text, nine participants showed a lack of understanding. Furthermore, it was shown that PSCTs had difficulties in determining the ranking of substituents and assigning the proper configuration. PSCT5 gave a response in **Figure 9**.

This was mostly due to the difficulties faced in orienting the drawings in such a way that priority is given to the highest-ranked group and subsequently assigning the appropriate R or S configuration to each stereocenter.

Question 6 and question 7 were follow-up questions to question 5. In particular, question 7 asked PSCTs to give reasons why some molecules are classified as enantiomers or diastereomers. However, the result shows that PSCTs (21 out of 33) experienced conceptual difficulties when responding to the question. Their responses showed a lack of comprehension of question 7. This result became evident during the interview. One PSCT narrated:

> "I could see that these three molecules have two stereocenters. However, I cannot really tell which one is a mirror image of the other. I have tried to orient these molecules just to answer the question, but then I had no option but to just guess the answer, which I got wrong. Yhoo. Bad luck to me" (PSCT 9).

This response indicates difficulties PSCTs experienced when assigning stereocenters to molecules and identifying and stating the relationships between enantiomers and diastereomers.

Question 8 inquired about the presence of chirality centers in cis-1,2-dimethylcyclobutane, and the location of its chirality, and requested a justification for the response. The study revealed that PSCTs (14 out of 33) showed a lack of comprehension of the subject and provided incorrect responses. PSCTs who provided incorrect responses had difficulty recognizing that the molecular arrangement of cis-1,2-dimethylcyclobutane exhibits chirality centers at the carbon atoms (C1 and C2) within the methyl-bearing ring. One PSCT provided an inaccurate response during the interview:

> "I think this molecule has a chirality center because I see a plane of symmetry. Hence, I responded that it is chiral" (PSCT 20).

This response is inaccurate. A carbon atom linked to four groups is needed to identify a chirality center in a molecule. Moreover, in order to ascertain the chirality of the molecule, one needs to examine the presence of a plane of symmetry. It is important to acknowledge that not all molecules with chirality centers exhibit chirality since meso compounds provide an exception to this generalization.

There were a few other questions, where PSCTs showed conceptual understanding of stereochemistry. For example, question 9 and question 10 required participants to specify the reagents that would be employed for the resolution of the compounds, namely,

(a) 1-phenyl-2-propanamine and

(b) 2,3-pentadienedioic acid.

The participants were further prompted to demonstrate the reactions implicated and indicate the preferred physical approach for separating the diastereomers. The feedback received from PSCTs, both in written form and during the interviews, suggests that PSCTs (10 out of 33 and 21 out of 33, respectively) demonstrated understanding in question 9 and question 10. However, the ability of PSCTs to accurately determine the outcome of the reaction between a racemic mixture of 1-phenyl-2-propanamine and the chiral acid (+)-tartaric acid (R, R) was shown to be inadequate. Few PSCTs demonstrated that the resulting reaction will produce a mixture of diastereomeric salts, which they can use to separate the diastereomers through crystallization, and then the salt is treated with a strong base (e.g., KOH) to recover the pure enantiomeric amine.

PSCTs' Misconceptions in Stereochemistry

According to the data shown in **Table 3**, PSCTs predicted chiral or achiral molecules in question 2. The majority of PSCTs (21 out of 33) provided responses that were incorrect, suggesting the presence of a misconception. One PSCT provided a response on the classification of a molecule as chiral during interview:

> "It is a forming the same image on the mirror as the original one is called to be chiral" (PSCT 3).

This response implies that the classification of a molecule as chiral was based on the presence of an atom with four distinct substituents. Their responses inferred a tetrahedral carbon atom with four distinct substituents, rather than perceiving the molecule as a whole entity.

Question 3 requested participants to determine the chirality of 3-methylhexane and provide a rationale for their response. However, PSCTs (23 out of 33) were unable to provide a satisfactory explanation for the chirality of the molecule. One PSCT provided a response:

> "The molecule is chiral because chiral molecules are molecules, which cannot be superimposed and the chiral center bonds with other molecules or compounds in their chain" (PSCT 12).

The response provided lacks specificity and fails to address the subject at hand. Some PSCTs further provided inaccurate responses by stating that the molecule is achiral due to its symmetry, resulting in the production of identical halves. Consequently, they claimed that the molecule has methyl and lacks four groups attached to the central atom.

Question 4 asked PSCTs to give a spatial diagram of (R)-2-chlorobutane and justify why this molecule is achiral or chiral. A total of 20 participants exhibited misconceptions as they were unable to accurately depict or articulate the observed phenomena correctly. During the interviews, One PSCT said:

> "Ranking the four substituents is my problem. If I have to place -H away from me, then the other substituents must be placed next to each other such that the direction of travel will be anticlockwise (left turn)" (PSCT 18).

The assertion made by PSCT18 is a misconception since it fails to consider the arrangement of the next three substituents in a clockwise (right turn) orientation, resulting in the molecule being tilted to allow the back hydrogen to become visible.

Question 5 required PSCTs to assign the configuration (either R or S) to molecules with chirality centers in the given compounds. The result shows that PSCTs had misconceptions in determining the ranking of substituents and assigning the proper configuration. This was mostly due to the difficulties faced in orienting the drawings in such a way that priority is given to the highest-ranked group and subsequently assigning the appropriate R or S configuration to each stereocenter.

In the second reaction of a 2,3-pentadienedioic acid mixture with a chiral base, PSCTs responded to no enantiomer production. This assertion is a misconception, as the reaction will yield a combination of diastereomeric salts, which may be effectively isolated by means of crystallization. Subsequently, the pure enantiomer acid can be recovered by subjecting it to the action of a powerful acid, such as hydrochloric acid

(HCl). Most PSCTs had limited knowledge of techniques for separating the mixture, aside from relying only on crystallization.

Methods to Improve PSCTs' Understanding of Stereochemistry & Organohalides

The third research question asked PSCTs to describe the strategies they require to enhance their understanding of organohalides and stereochemistry concepts.

The interviews revealed that PSCTs provided strategies that lecturers might employ to improve their comprehension of these concepts. PSCTs expressed a consensus need for assistance in obtaining instructional resources, support in synchronizing and aligning instructional materials with blended learning methods, activity-based problem-solving supports, such as worksheets, and the provision of other educational resources to assist their learning success. One PSCT explained:

> "This concept of stereochemistry is very difficult to understand. I suggest my lecturer to provide us with activities at the end of each lecture to assist us to practice most questions on the topic" (PSCT 2).

Participants also requested simulation lessons to enable them to understand the concept better. PSCTs were of the view that the integration of interactive technologies and online simulations will augment engagement and comprehension of the concepts under study, and it will further provide them with the opportunity to engage in experimentation and conceptual exploration in a virtual setting. This will ultimately enable them to actively participate in the learning process, fostering a more profound comprehension of chemical ideas.

PSCTs also mentioned the re-introduction of peer-assisted learning into their chemistry modules, where they will have a chance to teach one another the concepts some find difficult to learn. This will facilitate increased levels of active involvement among PSCTs and foster a more profound comprehension of conceptual knowledge.

DISCUSSION

The purpose of this study was to identify the conceptual and procedural knowledge of PSCTs in organohalides and stereochemistry and further to identify conceptual difficulties they might experience in these concepts. In addition, the study further identified any misconceptions PSCTs had when studying organohalides and stereochemistry and suggested strategies to enhance their achievements. These concepts were taught in the first block of the first semester. The current discourse is around the interplay between PSCTs' conceptual knowledge, conceptual difficulties, their misconceptions, and the constructivism theory proposed by Vygotsky, together with the relevant scholarly literature.

Research question 1 centered on the conceptual and procedural knowledge required by PSCTs to understand stereochemistry and mechanistic processes in organohalides. **Table 1** presented the factual, procedural, and conceptual knowledge assertions that were subjected to comparison with explanations provided by PSCTs, written text items, and interview transcripts. The finding indicates that PSCTs had little conceptual and procedural knowledge on the concepts taught. This implies that PSCTs encountered difficulties in understanding the topics taught. This further shows that the conceptual difficulties experienced by PSCTs arise from the fragmented knowledge structures exhibited by PSCTs while naming organic molecules, representing molecules using structures, visualizing three-dimensional spatial molecules, employing a combination of ideas during problem-solving, and encountering problems in understanding mechanistic processes. This finding aligns with the study conducted by Popova and Bretz (2018), which investigated students' comprehension of leaving groups and revealed that students exhibit fragmented frameworks of knowledge, leading to a diverse application of concepts during problem-solving. This finding provides further support for previous claims made by various authors regarding difficult topics in organic chemistry. These topics include the description and representation of organic compounds (Salame & Khalil, 2023), the characteristics of organic compounds (Anderson & Bodner, 2008), and the study of stereochemistry (Durmaz, 2018).

Nevertheless, some scholars have highlighted factors contributing to student conceptual difficulties, including ineffective instructional methods, reliance on memory, and insufficient subject knowledge (Anzovino & Bretz, 2015; Popova & Bretz, 2018; Xue & Stains, 2020). However, in the context of constructivist pedagogy, it is imperative for educators to acknowledge their students' prior knowledge and experience as a primary step. Galloway and Bretz (2015) advocate for the use of constructivism as a pedagogical approach inside the laboratory environment. According to their argument, the process of meaningful learning, a fundamental component of the constructivist approach, encompasses the amalgamation of cognitive processes, emotional responses, and behavioral actions. Through the implementation of laboratory experiences that foster meaningful learning, students are able to actively create their understanding of ideas related to organic chemistry.

The second research question focused on the misconceptions that PSCTs develop about stereochemistry and organohalides. The results indicate that PSCTs had misconceptions in many areas of organohalides and stereochemistry. These areas included: assigning configurations to molecules; predicting whether a molecule is chiral or achiral; recognizing stereocenters; understanding the spatial representation of stereoisomers; naming organohalides; and detecting mechanistic reactions of organohalides. This finding corroborates earlier findings by McClary and Bretz (2012) that the students who registered for the organic chemistry course experienced misconceptions in the course. The study further found that these misconceptions arose from students' prior knowledge, erroneous understanding, which contradicts factual scientific notions, and students shared information from textbooks. This finding corroborates earlier findings that highlighted the causes of students' misconceptions including prior knowledge, erroneous understanding, which often contradicts the already accepted scientific notions, textbooks, and information disseminated by instructors (Kose, 2008; Kumi et al., 2013). The process of identifying, analyzing, and purposefully resolving misconceptions held by students plays a vital role in supporting their progression from superficial descriptions and definitions to a more holistic and interconnected knowledge.

The erroneously notions and concepts held by students may be accurate, but many of them deviate greatly from the scientifically recognized viewpoint and are subjectively updated based only on sensory input (Gilmore et al., 2017). The theory of social constructivism acknowledges that knowledge is a product of social interactions and highlights the significance of addressing students' existing beliefs and misconceptions in the process of teaching and learning (Palincsar, 1998). This suggests that the focus of education is on individuals, with an emphasis on generating new information rather than passively acquiring knowledge from the teacher. Nevertheless, the results suggest that teachers, lecturers and curriculum designers should exercise caution when choosing explanatory language, especially when it comes to terms that possess divergent every day and scientific connotations. This is crucial as students rely on these everyday connotations to shape their comprehension of scientific concepts. Silva et al. (2019) suggest employing a board game as a means to actively include students in the teaching and learning processes.

The third research question asked PSCTs to express what they needed from their lecturers to enhance their conceptual understanding on organohalides and stereochemistry. The findings suggested support in synchronizing and aligning instructional materials with blended learning methods. Additionally, PSCTs sought activity-based problem-solving supports, such as worksheets, to assist their learning success. This aligns well with the constructivist approach of teaching and learning by involving learners in meaning making. Active learning is a teaching approach that encourages students to actively engage in the learning process through activities such as group discussions, problem-solving sessions, and hands-on experiments (York & Orgill, 2020). This approach promotes a deeper understanding of concepts by allowing students to apply their knowledge in real-world contexts, actively participate in their own learning, build on their prior knowledge, and facilitate the learning process (Berisha, 2020). By actively engaging with the material, students are more likely to retain information and develop critical thinking skills (Smith et al., 2005).

CONCLUSIONS & IMPLICATIONS

Organic chemistry necessitates students who possess the capacity to comprehend its principles both at the macroscopic and sub-microscopic scales, as well as the ability to establish connections between the symbolic representations employed at each level. Possessing a comprehensive conceptual and procedural knowledge of the subject is deemed an essential fundamental element in the pursuit of further studies.

This study was conducted with a cohort of 33 PSCTs from a whole class. The study revealed that a significant proportion of participants recognize the significance of conceptual knowledge and spatial ability in comprehending problems associated with organohalides and stereochemistry. Specifically, they perceive tasks involving mechanistic reactions, naming compounds, mental rotation, visualization of three-dimensional molecules, assigning priority functional groups to molecules, and identifying R and S configurations as particularly demanding. The findings indicate that, despite PSCTs receiving theoretical instruction on stereochemistry and organohalides, they did not possess a robust conceptual understanding of the subject. Furthermore, PSCTs have misconceptions regarding fundamental concepts in stereochemistry and organohalides and therefore are incapable of providing an appropriate procedural explanation for the concepts under discussion.

In order to foster an effective conceptual understanding of organohalides and stereochemistry, it is important for students to possess a comprehensive grasp of spatial skills, including mental rotation and the visualization of three-dimensional chemical molecules. Therefore, constructivist teaching approaches have the potential to facilitate the enhancement of students' spatial abilities through the provision of opportunities for practice and development in this domain. The theory of constructivism places significant emphasis on the active process of knowledge production by learners, which occurs through their interactions with the environment and their pre-existing knowledge, and the establishment of links between their existing knowledge and newly acquired information. An inherent limitation of the study was the use of a diminutive sample size. The current study did not choose a larger sample size. Primarily, this may be attributed to the absence of a broad sampling frame.

It is expected that PSCTs would actively engage in the process of meaning-making in the course of instruction, which could lead to the retention of chemistry concepts as they engage actively in the teaching-learning process. Therefore, the study recommends the use of differentiated instructions in combination with digital resources to enhance PSCTs' conceptual understanding of the subject and to reduce the occurrence of students' misconceptions. Hence, this study makes a valuable contribution to the scholarly discourse surrounding the enhancement of pedagogical practices to improve educational outcomes of students on organohalides and stereochemistry.

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