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Research on the Mental Model of Organic Chemistry Concepts of Chemistry Normal University Students from the Perspective of Senior High School-University Cohesion

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Abstract: The teaching cohesion between secondary school and university has long been a research focus for educators, while studies on how to effectively bridge organic chemistry between these two educational stages remain scarce. Furthermore, the new curriculum standard lists "chemical concepts" as an important component of the core disciplinary competencies that need to be mastered. As future frontline secondary school teachers, normal university students are required to have a deeper grasp of chemical concepts. Based on this, this study combines text analysis with a two-tier paper-and-pencil test to evaluate the mental models of organic chemistry held by normal university students, focusing on various chemical concepts such as the element concept and structure concept. According to the test results, seven types of defective mental models are summarized, and corresponding teaching suggestions are put forward, aiming to lay a solid foundation for normal university students' subsequent chemistry learning and teaching practice.

Keywords: Mental Model; Chemical Concepts; Organic Chemistry; Senior High School-University Cohesion; Chemistry Normal University Students

1. Problem Statement

The General High School Chemistry Curriculum Standard (2017 Edition, Revised in 2020) and the Compulsory Education Chemistry Curriculum Standard (2022 Edition) both list "chemical concepts" as an important component of the core competencies of chemistry[1-2]. The compulsory education curriculum standard clearly defines chemical concepts as the viewpoints and methods students form for understanding substances from a chemical perspective, after deeply comprehending and mastering chemical knowledge and concepts and applying them continuously. The core competencies in the high school new curriculum standard build on those of compulsory education and are refined into specific dimensions such as "macroscopic identification and microscopic exploration" and "change concept and equilibrium thinking", with the core competencies of the two stages being consistent and coherent. Based on the curriculum standards and the research of scholars such as Bi Hualin[3] and Zhu Yujun[4], chemical concepts can be categorized into the element concept, structure concept, equilibrium concept, STSE concept, classification concept, etc.

As an individual's internal cognitive representation of the external world, a mental model reflects how students understand chemical concepts and their thinking processes, serving as an important tool for exploring their cognitive structure[5]. Johnson-Laird[6] proposed that mental models, as cognitive representations stored at different levels of the memory system, are psychological mechanisms formed by individuals in the process of interpreting experiences. In other words, mental models are the problem-solving thinking patterns people demonstrate after acquiring certain experience.

Foreign scholars have conducted extensive research on mental models, covering topics such as atoms and molecules, metallic bonds, and acids and bases[7-9], and have proposed relevant teaching methods based on their findings. In domestic research, the focus has often been on empirical investigations of middle school students' mental models of substances such as methane, ethanol, and aromatic hydrocarbons[10-12].

Despite the extensive research on mental models both domestically and internationally, studies on the mental models of organic chemistry concepts among normal university students remain limited, making it difficult to meet the dual needs of disciplinary literacy and teaching ability cultivation in teacher education. As future chemistry teachers, the formation of chemical concepts among chemistry normal university students directly influences the construction of such concepts in their future students.

Organic chemistry, as a core content spanning middle school and university, covers a comprehensive range of chemical concepts, making it an ideal carrier for studying the cohesion of chemical concepts. Therefore, this study focuses on organic chemistry and uses a two-tier test to explore the mental models of chemical concepts held by chemistry normal university students in the context of high school-university cohesion. The aim is to reveal the defective mental models of chemical concepts among normal university students, analyze their causes, and propose teaching suggestions to promote the coherent development of chemical concepts in normal university students.

2. Research Objects and Methods

2.1 Research Objects

This study selected a total of 94 students majoring in Chemistry (Teacher Education) from the 2021 cohort at Guangdong University of Education as research subjects. To control for knowledge differences among participants, all subjects had completed both high school chemistry and university organic chemistry courses, with their grade point averages (GPA) in the university Organic Chemistry course ranging between 3.0 and 3.5. This was done to reduce the volatility and randomness of results, thereby enhancing the reliability and generalizability of the conclusions.

2.2 Research Methods

This study primarily combined text analysis and paper-and-pencil tests to examine the mental models of chemical concepts in organic chemistry among normal university students.

First, define the content and scope. By carefully reviewing sections of the new curriculum standard related to chemical concepts, analyzing high school and university organic chemistry textbooks, and consulting relevant literature, the connections between organic chemistry knowledge points and chemical concepts across the two educational stages were identified, and the conceptual knowledge points for this study were formulated. Taking the substance concept as an example below, the specific connotations of chemical concepts and the cohesion of corresponding high school and university knowledge points are illustrated.

Basic Chemical Concepts		Connotation	Specific Knowledge
Substance Concept	Element Concept	1.Substances are composed of elements.	For example: Carbohydrates are compounds composed of three elements, namely carbon (C), hydrogen (H), and oxygen (O).
	Particulate Concept	1.Substances are constituted by particles.	For example: Organic substances are substances in which various particles are connected via chemical bonds.
		2.Interactions exist among particles.	For example: hydrogen bonds, van der Waals forces, inductive effects, conjugation effects, field effects, bond polarity and dipole moments, covalent bonds (π bonds, σ bonds), valence bond theory, etc.
	Structure Concept	1.Substances have specific structures, which reflect the concept of chemical space.	For example: Bond lengths and bond angles determine the three-dimensional shapes of molecules, as well as isomers, carbon skeletons (chain and cyclic), and the saturation degree of carbon atoms.
		2.The composition and structure of substances determine their properties, and properties determine their applications.	For example: functional groups, types of chemical bonds, interactions between groups, and changes in the polarity of chemical bonds within functional groups, which in turn affect the properties of functional groups and substances.

Second, collect misconceptions. By reviewing a large volume of literature and conducting in-depth analysis of curriculum standards and textbooks, the misconceptions existing in normal university students' understanding of chemical concepts were identified. For example, the statement "the properties of a substance change when an element in its structure is substituted" belongs to the structure concept; however, normal university students tend to be distracted by the wording in the question stem and fail to identify the correct chemical concept—for instance, they may mistakenly classify it as the element concept.

Third, design the questionnaire. To enhance the practicality and authenticity of this study, the researcher conducted an on-site questionnaire survey at a normal university in Guangdong Province. Based on the misconceptions identified in the literature review, a two-tier questionnaire was developed. The paper-and-pencil test adopted a two-tier diagnostic format:

- The first tier (content tier) consisted of single-choice or multiple-choice questions with 4 options, which mainly aimed to assess normal university students' mastery of knowledge and chemical concepts;
- The second tier (reasoning tier) provided possible justifications for the answers to the first-tier questions.

Fourth, test the reliability and validity of the content. A two-way specification table was formulated based on the diagnostic content, scope, and the designed two-tier questionnaire.

Knowledge Points	Comprehension	Application	Analysis
Element Concept	1		
Particulate Concept		2	
Structure Concept	3		
Equilibrium Concept	6		4
Process Concept			4, 8
STSE Concept		7	
Energy Concept	5	9	
Classification Concept		10	

To verify whether these 10 test items fully cover the core content and meet the requirements for measuring mental models, 5 experts in chemistry pedagogy and instructors teaching organic chemistry were invited to review and revise the items. Each item was evaluated across three dimensions: content relevance, logical rationality, and difficulty appropriateness, using a 4-point rating scale (1 = completely irrelevant, 4 = highly relevant). The Item-Content Validity Index (I-CVI) and Scale-Content Validity Index (S-CVI) were then calculated.

An Intraclass Correlation Coefficient (ICC) analysis of the experts' scores across the three dimensions indicated a high level of consistency among their evaluations. The calculation results showed that the S-CVI = 0.96, and the I-CVI values of 9 items were all ⩾ 0.80. However, the I-CVI of Item 6 was only 0.6, suggesting that the wording of Item 6 needed revision. The experts provided comments that the specific content of the substitution mechanism should be modified. They noted that Option B (keto-enol equilibrium) and Option C (esterification equilibrium) were consistent with the equilibrium concept, but Option A (nucleophilic substitution mechanism) had an ambiguous distractor description, which was likely to cause confusion between the process concept and the equilibrium concept.

In summary, the results demonstrate that the questionnaire has a certain degree of reliability and can basically meet the needs of this study.

Item Number	Core Measured Concept	ICC Value	Reliability Evaluation
1	Element Concept	0.793	Good
2	Particulate Concept	0.73	Good
3	Structure Concept	0.831	Excellent
4	Equilibrium Concept、Process Concept	0.78	Good
5	Energy Concept	0.802	Excellent
6	Equilibrium Concept	0.924	Excellent
7	STSE Concept	0.785	Good
8	Process Concept	0.819	Excellent
9	Energy Concept	0.823	Excellent
10	Classification Concept	0.852	Excellent

Fifth, test implementation. A total of 94 questionnaires were distributed, and 94 valid questionnaires were retrieved, resulting in a 100% valid response rate. Prior to the formal test, the researcher briefly explained the research purpose and content of the test paper and invited normal university students to complete the test on a voluntary basis. After the test was completed, the test results were analyzed and statistically processed. SPSS 22.0 was used to conduct a reliability analysis of the questionnaire. The Cronbach's α coefficient was 0.742, and the I-CVI values of all 10 items were ⩾ 0.80, which basically met the research requirements.

Different from the traditional two-tier paper-and-pencil test, a blank option was added to the second tier to allow students to express ideas beyond the provided options, thereby reducing the errors in research results caused by fixed reasoning options. [13]

Example Item 1 (Multiple Choice)

Which of the following examples reflect the Element Concept? (AB)

A. Carbohydrates are compounds composed of three elements: carbon (C), hydrogen (H), and oxygen (O).

B. All organic compounds contain carbon; thus, organic compounds are carbon - containing compounds.

C. Heterocyclic compounds are organic compounds with heterocyclic structures in their molecules. In addition to carbon atoms, the atoms forming the ring include at least one heteroatom.

D. When 1, 2, or 3 hydrogen (H) atoms in an NH_3 molecule are substituted by alkyl groups, primary amines (1°), secondary amines (2°), and tertiary amines (3°) are generated respectively, whose properties are completely different from those of NH_3.

Please select the reasons for your choice (b, d).

a. Heterocyclic compounds contain elements such as N, O, and S.

b. When a certain element is mentioned, one can associate it with a series of substances containing that element.

c. The substitution of H elements in the material structure will inevitably lead to changes in chemical properties.

d. It reflects that all substances are composed of specific types of elements.

e. Other reasons: _______________

Example Item 2 (Single Choice)Which chemical concept is reflected by both of the following statements? (D)

① The first carbon atom carries a relatively high positive charge "δ+" , the second carbon atom carries a partial positive charge "δ++" , and the third carbon atom carries a weaker positive charge "δ+++" . This characteristic is transmitted along the carbon chain and attenuates or disappears rapidly as the chain length increases.

② An acetaldehyde solution contains countless acetaldehyde molecules, and each acetaldehyde molecule consists of one oxygen atom, two carbon atoms, and four hydrogen atoms.

A. Structure Concept

B. Process Concept

C. Energy Concept

D. Particulate Concept

Please select the reasons for your choice:(c)

a. Both chloropropane and acetaldehyde molecules have unique structures.

b. The Cl in chloropropane tends to dissociate in specific reactions, and each acetaldehyde molecule has its respective energy.

c. Acetaldehyde molecules are composed of the corresponding atoms, and interactions exist in chloropropane.

d. Molecular motion processes occur in acetaldehyde solution, and chain transmission reflects a process.

e. Other reasons: _______________

Based on the extended answers and misconceptions of the respondents reflected in the test results, a targeted analysis was conducted on the internal logic and underlying reasons of the normal university students' relevant cognition. This analysis aimed to clearly depict their mental models and conduct a preliminary exploration of the causes behind these models. Meanwhile, by incorporating relevant middle school knowledge and university knowledge into the options, the chemical concepts under the context of knowledge connection were reflected.

3. Results and Analysis

The results of the two-tier test showed that students failed to fully grasp the specific and exact connotations of various chemical concepts. Instead, they merely interpreted these concepts literally, leading to inaccurate explanations.

In terms of option selection, many students chose the correct answers by guessing, but at the same time selected other distracting options. In addition, students exhibited certain degrees of forgetting or misunderstanding of relevant organic chemistry knowledge, which also resulted in their failure to select the correct options.

The researcher will generalize and analyze the mental models of normal university students regarding organic chemistry concepts based on the test results, with a primary focus on the data content accounting for more than 5% in the reasoning tier of the test. Data with a proportion of less than 5% will be excluded due to insufficient representativeness[14]. Further, this study will summarize the defective mental models of normal university students characterized by missing knowledge elements and erroneous knowledge content. When describing these defective models, in-depth reflections will be provided on how normal university students understand chemical concepts within the context of organic chemistry.

3.1 Inductive Analysis of Models Related to the Element Concept

Categories of Mental Models	Content	Percentage/%
Scientific Model	Substances are composed of elements. For example, carbohydrates are compounds made up of three types of elements.	39.36
	When a certain element is mentioned, one can associate it with a series of substances containing that element. For example, all organic compounds contain carbon, and thus organic compounds are carbon-containing compounds.	21.28
Defective Model of Particulate-Element Concept	Classify the heteroatoms contained in heterocyclic compounds into the concept of elements.	44.68
Defective Model of Ambiguous Concept Definition	Misclassify other chemical concepts into the Element Concept. For example, students erroneously regard the statement that "the substitution of a certain element in the material structure will inevitably lead to a change in chemical properties" as a reflection of the Element Concept.	26.60

As can be seen from the table, 44.68% of normal university students had an ambiguous understanding of the boundary between the macroscopic and the microscopic. They regarded elements, molecules and atoms as equivalent and interchangeable concepts in application. In the context of the Element Concept, these students tended to overlook the fact that elements belong to the macroscopic level, and confused them with molecules, atoms and other entities belonging to the microscopic level, failing to distinguish clearly between the macroscopic and the microscopic. This indicates that normal university students had cognitive biases in the concepts of the Element Concept and the Particulate Concept, and they confused the macroscopic concept of elements with the microscopic structure of substances. This type of mental model is thus named the Defective Model of Particulate-Element Concept.

In addition, 26.60% of normal university students selected misleading options that described other chemical concepts rather than the Element Concept. The presence of the word "element" in the options tended to mislead their judgment. The underlying reason for this was their insufficient proficiency in defining and applying various chemical concepts. This type of mental model is therefore named the Defective Model of Ambiguous Concept Definition.

3.2 Assessment of Model Generalization Related to the Particulate View of Matter

Categories of Mental Models	Content	Proportion/%
Scientific Models	Matter is composed of particles such as atoms, molecules, and ions, among which interactions exist. For example: the composition of an acetaldehyde molecule; the shift of electron density in the induction effect.	53.19
Image-Structure Deficit Model	When encountering images related to organic substances, there is a tendency to automatically associate the image with the structure of the substance, overlooking the representation of particles within it. For example, viewing the chain transmission of the inductive effect as a manifestation of the substance's structure, or interpreting van der Waals forces as interactions between particles.	29.79
Conceptual Definition Ambiguity Deficit Model	Terms such as "molecular motion process" and "chain transfer process" are categorized under the process perspective due to their inclusion of the word "process."	11.70

As shown in the table, 29.79% of teacher candidates tend to unconsciously associate the schematic model images presented in the question solely with the structural perspective, failing to accurately determine which specific chemical concept is actually being described based on the information provided in the question. In this question, teacher candidates tend to confuse the particulate view with the structural view, misinterpreting the relevant material schematic diagrams as involving the examination of structure and properties. Such a mental model can be termed the "Image-Structure Deficit Model."

11.70% of teacher candidates are prone to being misled by option labels that contain terms superficially similar to the names of chemical concepts. For instance, when the word "process" appears, they are influenced by its literal meaning and directly associate it with the "process perspective," while overlooking the true conceptual meaning of the "process perspective," thereby failing to select the correct answer. The underlying issue is an insufficient familiarity with the definitions and applications of various chemical concepts, leading to reliance on literal interpretations. Consequently, this type of mental model is termed the "Conceptual Definition Ambiguity Deficit Model."

3.3 Assessment of Model Generalization Related to the Equilibrium Perspective

Categories of Mental Models	Content	Proportion/%
Scientific Models	The fundamental concept of the equilibrium perspective is that chemical change processes have limits. For example, the monochlorination reaction of methane is a limited process and cannot proceed to completion.	40.43
	Dynamic equilibrium under specific conditions can be disrupted by altering certain factors.	42.55

Continuation Table:

Categories of Mental Models	Content	Proportion/%
Transition State-Equilibrium Deficit Model	The transition state in a chemical reaction mechanism is interpreted as implying that the reaction should reach a static equilibrium, with the misconception that static equilibrium refers to equal rates between fast and slow steps.	36.17
Conservation-Limit Deficit Model	Only when an organic chemical reaction reaches its limit are the principles of element conservation, mass conservation, and energy conservation fully satisfied.	32.99

As indicated in the table, 36.17% of teacher candidates confuse the concept of chemical equilibrium with reaction rates—specifically, they equate the equilibrium within a step (e.g., equal forward and reverse rates in a fast step) with equal rates between different steps. This indicates that teacher candidates fail to correctly understand that when a chemical reaction reaches its limit (equilibrium), the overall forward and reverse reaction rates become equal. Furthermore, a fundamental characteristic of chemical equilibrium is its dynamic nature. The existence of a transition state is not inherently related to whether equilibrium is reached, as reactions continue to proceed through transition states even under equilibrium conditions. Therefore, this type of mental model is termed the "Transition State-Equilibrium Deficit Model."

32.99% of teacher candidates hold ambiguous or confused notions regarding the concepts of conservation perspective and equilibrium perspective. They mistakenly equate the conditions for reaching equilibrium with the conservation of elements and mass before and after a reaction, primarily reflecting a deviation in their understanding of the equilibrium perspective by interpreting the invariance of element types and quantities as a form of equilibrium. Therefore, this type of mental model is termed the "Conservation-Limit Deficit Model."

3.4 Assessment of Model Generalization Related to the Process Perspective

Categories of Mental Models	Content	Proportion/%
Scientific Models	The initial state, transition state, and final state together constitute the process of chemical change, reflecting a conceptualization of chemical time. For example, in the two-step reaction mechanism of methane monochlorination, the initial state, transition state, and final state constitute the process of chemical change.	50.00
Knowledge-Deficit Model	When evaluating conceptual understanding, knowledge-related errors in organic chemistry may arise, such as the misconception that catalysts accelerate reaction rates by altering the energy of the initial and final states.	24.47

24.47% of teacher candidates demonstrate misconceptions regarding the role of catalysts, erroneously attributing the increase in reaction rate to the catalyst altering the energy of reactants or products. These teacher candidates possess a superficial understanding of catalysts—they recognize that catalysts accelerate reaction rates but fail to grasp the underlying mechanism from the perspective of transition state theory, specifically that catalysts function by lowering the activation energy to enhance the reaction rate. Therefore, this type of mental model is termed the "Knowledge-Deficit Model."

3.5 Assessment of Model Generalization Related to the STSE (Science-Technology-Society-Environment) Perspective

Categories of Mental Models	Content	Proportion/%
Scientific Models	Chemistry is closely interconnected with science, technology, society, and the environment, and it serves as a central discipline within the natural sciences. For example, the emergence of organic synthetic materials represents a significant breakthrough in the history of material development.	65.96
Knowledge-Deficit Model	When assessing conceptual understanding, knowledge-related errors in organic chemistry may arise, such as misinterpreting hydrogenation as a reaction related to clean energy that aligns with the principles of green chemistry, thereby incorrectly categorizing it under the core ideas of the STSE perspective.	21.28

21.28% of teacher candidates demonstrate a lapse in memory regarding the knowledge of hydrogenation reactions—specifically, that hydrogenation involves addition or decomposition reactions of organic compounds with hydrogen under catalytic conditions. Instead, they associate the term "hydrogenation" with hydrogen as a clean energy source, leading them to select concepts related to green chemistry. This essentially stems from an incomplete grasp of certain organic chemistry knowledge points, leading to the misselection of concepts. Therefore, this type of mental model is termed the "Knowledge-Deficit Model."

4. Instructional Recommendations for Enhancing Chemistry Teacher Candidates' Understanding of Chemical Concepts

Under the new circumstances of educational development, the requirements for secondary school students in the field of chemistry have moved far beyond rote memorization and mechanical imitation. Greater emphasis is now placed on the effective implementation of students' core competencies, marking a shift from "knowledge acquisition" to "capacity building". The development of students largely depends on the guidance and direction provided by teachers. This implies that educators must possess an accurate and profound understanding of the core competencies of the discipline, and be adept at integrating these competencies into their teaching practice. As a key component of core competencies, chemical concepts should be studied and applied by chemistry teacher candidates—the emerging force entering the teaching profession—to adequately prepare for becoming qualified educators in the future.

As noted in reference[15] regarding the instructional transition between secondary school and university inorganic chemistry, few teachers actively compare and connect the knowledge points between these two levels, often overlooking the importance of curricular continuity. To address this, university instructors should familiarize themselves with high school content and, in accordance with the cognitive patterns of teacher candidates, advance the teaching of new knowledge while revisiting prior learning. As discussed in reference[16], a study focusing on the theme of organic chemical properties explored the transition between secondary and university chemistry education. It suggested that university instructors should acknowledge the uneven educational backgrounds of first-year students and, when necessary, conduct diagnostic assessments prior to instruction. This approach aims to address the existing gaps and redundancies in the teaching of organic chemical properties between secondary and tertiary education.

Based on the research findings and the issues highlighted in the existing literature, the instructional recommendations derived by the author are as follows:

4.1 Optimizing University Curriculum Design to Strengthen the Articulation and Deepening of Chemical Concepts

In university-level organic chemistry courses, emphasis should be placed on bridging the content with the chemical concepts taught in high school, while further deepening students' understanding of these fundamental chemical principles.Incorporating academic lectures or specialized courses related to chemical concepts into the professional curriculum, with a focus on elucidating the meaning of chemical concepts and their practical applications in secondary chemistry teaching, will help teacher candidates systematically master the theoretical framework of chemical concepts. In organic chemistry courses, university instructors should familiarize themselves with the content covered in secondary education and clearly identify points of articulation between high school and university-level knowledge. For example, the well-established principle of "structure determines properties", already known to teacher candidates, can be systematically linked to newly introduced concepts at the university level, such as reaction mechanisms and electronic effects. This approach guides students to review prior knowledge from secondary education while progressively integrating chemical concepts into the advanced topics encountered in higher education.

4.2 Enriching Teaching Practice Models to Facilitate the Internalization and Application of Chemical Concepts

University instructors should employ diversified teaching practices to help teacher candidates translate chemical concepts into the ability to solve real-world problems. This can be achieved by designing experiment projects centered on chemical concepts, such as using reaction mechanism exploration (e.g., SN1/SN2 reactions) to guide students in understanding the "process perspective" and "equilibrium perspective", and reinforcing the "structural perspective" through spectroscopy analysis experiments. Teacher candidates should be encouraged to participate in activities such as chemistry teaching seminars and organic chemistry knowledge competitions, where they can exchange insights on teaching cases related to chemical concepts with frontline educators or researchers, thereby broadening their cognitive perspectives.In microteaching sessions, topics related to "the construction of chemical concepts" can also be incorporated to cultivate the ability of chemistry teacher candidates to translate chemical concepts from theory into practical teaching behaviors.

4.3 Refining the Assessment System for Chemical Concepts to Strengthen Teacher Candidates' Reflective and Transfer Abilities

In chemistry bridging courses between university and secondary education, instructors can design process-oriented assessment tasks—such as creating courseware, developing lesson plans, or writing research papers that incorporate chemical concepts—to diagnose students' mastery of these concepts. Meanwhile, chemistry teacher candidates should be effectively guided to reflect on both classroom learning and homework assignments, enabling them to transfer chemical concepts into future teaching practices. They can be required to analyze how chemical concepts are embodied in secondary school organic chemistry textbooks based on their university studies and propose corresponding instructional improvement strategies.

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