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Assessment of conceptual understanding in student learning of evaporation

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Developing a deeper understanding of scientific concepts is one of the primary goals of science education. To improve students' conceptual understanding, it is necessary to explore the major characteristics of their learning process. Informed by previous work on conceptual understanding, this study focuses on the concept of evaporation, exploring the level division of students' conceptual understanding of evaporation and the development of corresponding test questions. The level-based conceptual understanding assessment was tested on 721 seventh-grade Chinese students before and after the evaporation lesson. The results of quantitative and qualitative analyses indicated that the students' conceptual understanding of evaporation could be divided into three progression levels. Students with a low level of understanding only mechanically remembered the definition of evaporation and could identify evaporation phenomena in their daily lives based on memorized examples. Students with an intermediate level of understanding grasped not only the definition of evaporation but also the factors affecting the evaporation rate. Students with a high level of understanding understood the microscopic nature of evaporation and could explain how these three factors affect the evaporation rate from a microscopic perspective. This study also provides further evidence of the value of grasping the nature of concepts in conceptual understanding.

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I. INTRODUCTION

Recently, there has been a worldwide wave of science education reforms aimed at cultivating students' scientific literacy [1–3]. Students' deep understanding of scientific concepts is considered the core foundation of their scientific literacy [4–6]. Therefore, helping students understand scientific concepts through effective teaching methods has become an important issue in science education. Many previous studies have pointed out that identifying the main characteristics and development processes of students' conceptual understanding is a prerequisite for effective concept teaching [7,8]. For example, Xu *et al.* developed a conceptual framework and set of matching questions to map high school students' understanding of momentum [8]. This study represents a further attempt in this direction by exploring an effective approach to assess students' understanding of a certain scientific concept.

This study focuses on evaporation, a phase-change process from liquids to gases that involve intricate macroscopic and microscopic changes. The main reasons for choosing this concept are as follows. First, evaporation is a core concept of junior high school science courses. Learning about evaporation can support students' understanding of the water cycle in nature, the conservation of mass during phase changes, and the particle structure of matter [9–11]. Second, lessons about evaporation are presented in the seventh grade according to China's Compulsory Education Science Curriculum Standards. These science curriculum standards require seventh-grade students to identify evaporation phenomena, master the characteristics of evaporation, and explain the evaporation process using a microscopic particle model. However, according to previous interviews, many frontline science teachers have reported that learning about evaporation is a challenge for seventh-grade students, especially with regard to applying a microscopic particle model to explain macroscopic phenomena. Most science teachers do not conduct accurate assessments, so their judgments are qualitative and possibly imprecise. Therefore, an accurate assessment of students' conceptual understanding of evaporation is vital. After reviewing the related literature, it was found that junior high school students have many difficulties in learning about evaporation. Most students are limited to memorizing the definition of evaporation and fall into the trap of mechanical memory and extraction when solving related problems [12–15]. In particular, it is difficult for students to understand the nature of evaporation (i.e., the molecules in the surface layer of a liquid leave the liquid system and enter the air) [16–18].

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These findings are consistent with those reported by frontline science teachers in China. Finally, although various approaches for assessing conceptual understanding have been developed, relatively little research has assessed students' conceptual understanding of evaporation [19–21]. Therefore, this study fills a gap in the existing literature to a great extent.

Based on a literature review and expert consultations, this study divided junior high school students' conceptual understanding of evaporation into three levels. Using these three levels of conceptual understanding as a foundation, a series of test questions was created and applied to assess students' conceptual understanding of evaporation. In summary, the purposes of this study are as follows: (i) Construct a level division to categorize students' conceptual understanding of evaporation. (ii) Develop and implement an assessment based on these levels to analyze the characteristics of students' conceptual understanding of evaporation.

II. LITERATURE REVIEW (STUDENT LEARNING OF EVAPORATION)

Concept learning has consistently been an important topic in the field of science education. Researchers believe that before learning new scientific concepts, students spontaneously form related prior knowledge in their minds through repeated observations and experiences of various natural phenomena. This prior knowledge is the cognitive foundation on which students learn new scientific concepts. Some of this prior knowledge may reflect the nature of correct scientific concepts, but most of it is vague or even incorrect [22,23]. Specifically, evaporation is a common physical phenomenon. Previous studies have shown that most junior high school students can name this phenomenon and describe the evaporation process in simple language, such as water gradually decreasing and turning into water vapor [24–26]. However, many students do not know exactly what water vapor is and often confuse it with the common "white fog" in daily life [24]. According to China's Compulsory Education Science Curriculum Standards, after the evaporation lesson, seventh-grade students should be able to determine that the "white fog" is not water vapor but small droplets. Previous research has also shown that junior high school students have an incomplete understanding of how to accelerate or slow evaporation. Students appear to develop incorrect ideas about evaporation based on their own life experiences, such as mistakenly believing that larger volumes of water evaporate more slowly [27,28]. Even students who already have a knowledge foundation of particle theory make mistakes in their interpretations of the nature of evaporation [29–33]. For example, a common misconception among students is that during the evaporation process, the size of the particles in different states changes. As mentioned above, many Chinese frontline science teachers have found that junior high school students have difficulties learning about evaporation, which provides further evidence of the realistic dilemmas reported in previous research.

The traditional method of teaching evaporation focuses on helping students mechanically memorize the definition of evaporation and the surface features of the evaporation phenomenon but does not guide students toward an actual understanding of the physical process of evaporation [34,35]. This suggests that traditional teaching of evaporation neglects the development of students' conceptual understanding. Recently, innovative activities have emerged in the teaching of evaporation to enable students to engage in meaningful learning [36–38]. These activities generally start with familiar life experiences and encourage students to explore the evaporation phenomenon and the influencing factors that affect the evaporation rate through experiments, thereby helping them understand the concept of evaporation. Relevant studies have found that students' conceptual understanding of evaporation can be improved through such exploratory activities, but their understanding does not include the nature of evaporation [39,40]. Teaching strategies, such as particle modeling, role playing, and probing questions, have been applied to promote students' understanding of the nature of evaporation [41–44]. However, most teachers still lack the awareness to guide students to understand evaporation and its influencing factors at the microscopic level. As a result, the microscopic representation of the nature of evaporation has not been adopted as the core teaching content.

As suggested by the above review, researchers have recognized that evaporation is a difficult concept to learn. Therefore, it is necessary to explore the progressive process of students' conceptual understanding of evaporation. Previous studies have only roughly and preliminarily analyzed the difficulties and fragmented characteristics of students' conceptual understanding of evaporation, but have not formed systematic and precise assessment approaches and tools, thus limiting teachers from taking targeted teaching interventions. To enrich existing research from a new perspective, this study aims to develop a progressive division of students' conceptual understanding of evaporation and corresponding questions to systematically analyze students' conceptual understanding of learning about evaporation.

III. THE LEVEL DIVISION FOR MAPPING OUT STUDENTS' CONCEPTUAL UNDERSTANDING IN LEARNING EVAPORATION

A. Method of the level division

Studies on scientific concept learning have always focused on analyzing the developmental process of students' conceptual understanding and have attempted to establish a level division of students' conceptual understanding. For example, the structures of the observed learning outcome (SOLO) taxonomy theory and the learning progression (LPs) theory divide students' conceptual understanding into different levels and clearly describe the specific performance of students at each level [45,46]. In recent years, many studies have constructed conceptual framework models as the basis for dividing and assessing students' conceptual understanding levels [47–49]. Through a literature review and expert consultations, existing studies have constructed conceptual frameworks for scientific concepts such as momentum, buoyancy, and Newton's third law [50–52]. Based on these conceptual frameworks, researchers have divided the levels of students' conceptual understanding of the corresponding concepts. Considering the complexity of scientific concepts, the conceptual framework and the level division of a particular scientific concept are not unique. Their construction should be based on the principle of appropriateness.

The learning requirements for the study of evaporation in China's Compulsory Education Science Curriculum Standards are progressive. Initially, evaporation is introduced to the students as a simple natural phenomenon. With further learning, teachers guide students to explore more complex knowledge about evaporation, including how evaporation is affected by other factors and how it can be explained from a microscopic perspective. However, the learning requirements for evaporation in curriculum standards are general and should be further refined to measurable levels.

Based on the above analysis and literature review, an expert group composed of three science education experts and three senior science teachers (the three experts are well-known scholars in the field of science education, particularly skilled in the assessment of students' conceptual understanding and related instruction research, and the three frontline teachers have been teaching for more than ten years and all have rich experience in the teaching of evaporation) participated in the level division through consultation and demonstration. The students' conceptual understanding of evaporation was divided into three levels.

B. The three levels of students' conceptual understanding in learning evaporation

1. Low level: Mechanical memorization of the definition of evaporation

Learning scientific concepts is a complex cognitive activity that usually begins with students' perceptual experience [53,54]. In this study, the evaporation of liquids was a physical phenomenon that students often observed. For example, the washed hair was dried using a hair dryer, the wet clothes were then dried in the sun, and the spilled water slowly disappeared. According to interviews with teachers and students, junior high school students have accumulated large amounts of relevant factual information in their heads. In the initial stage of concept learning, teachers explained some typical evaporation phenomena in daily life and introduced the definition of evaporation: evaporation is a slow vaporization phenomenon that can occur at any temperature on a liquid surface. Under the guidance of teachers, most students can memorize the definition of evaporation mechanically and construct a preliminary correspondence between concrete phenomena and the concept of evaporation. Based on mechanical memorization, these students can identify which phenomena in daily life constitute evaporation and can correctly answer relevant questions in familiar situations. In summary, the expert group determined that the low level of understanding of evaporation is reflected by students' ability to mechanically remember the definition of evaporation and identify evaporation phenomena in real life based on their daily life experiences. However, these students have not yet developed a scientific understanding of evaporation. The conceptual understanding of students at this level is summarized in Fig. 1.

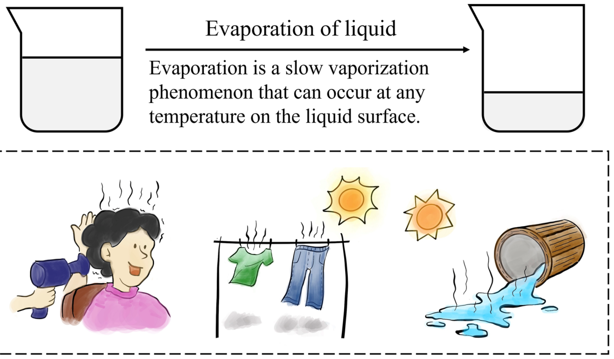


FIG. 1. Low level of understanding of evaporation.

2. Intermediate level: Grasp of the three major factors that affect the evaporation rate

Previous studies have shown that the development of students' conceptual understanding is not a direct leap from the previous level to the next but rather a continuous process [55,56]. Many students' understanding of evaporation is intermediate, between that of low and high levels. When students learn about evaporation, teachers can guide students to explore the influencing factors of the evaporation rate through experiments to help students improve their conceptual understanding of evaporation. Using the control variable method, some students discovered and understood that the three factors that affect the evaporation rate are the temperature of the liquid, surface area of the liquid, and air velocity on the liquid surface, and that the evaporation rate is positively correlated with them. These students cannot only predict the evaporation rate according to these three factors but also infer changes in the three influencing factors according to the evaporation rate. Occasionally, these students answered the questions correctly in complex situations, as if their conceptual understanding of evaporation had reached a new, higher level. However, the scientific reasoning behind solving these problems remains mechanical. Thus, the expert group determined that the intermediate level of understanding of evaporation is that students can grasp not only the definition of evaporation but also the factors that affect the evaporation rate and the effects of these factors. The conceptual understanding of students at this level is summarized in Fig. 2.

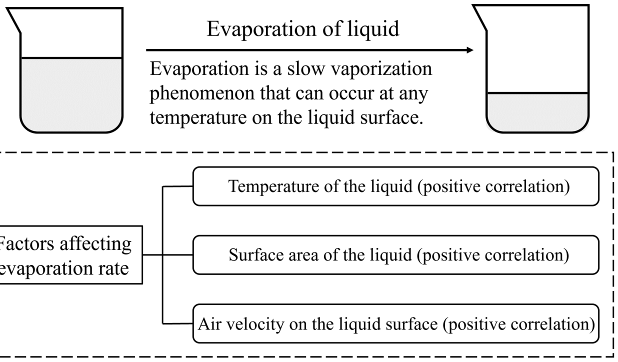


FIG. 2. Intermediate level of understanding of evaporation.

3. High level: Understanding of the nature of evaporation from a microscopic perspective

In the process of increasing students' conceptual understanding of evaporation to a higher level, teachers further help students explain the evaporation phenomenon at the microscopic level through pictures, molecular models, or multimedia technologies. From a microscopic perspective, matter is composed of irregularly moving molecules. Some molecules with high velocities in the liquid surface layer can break free from the constraints of other molecules and enter the air. The influence of the liquid temperature, liquid surface area, and air velocity on the liquid surface on the liquid evaporation rate can also be explained by the microscopic nature of evaporation. As the temperature of the liquid increases, the thermal motion of the molecules that make up the liquid intensifies. Molecules with higher velocities are more likely to overcome the attraction of other molecules during continuous motion, leaving the liquid surface to enter air. Therefore, the higher the temperature is, the more molecules escape from the liquid surface per unit time, which is reflected in the macroscopic phenomenon: the higher the liquid temperature, the faster it evaporates. As the surface area of the liquid increases, the number of molecules in the surface layer of the liquid also increases, and more molecules escape from the liquid surface to the air per unit time. This is reflected in another macroscopic phenomenon: the larger the surface area of the liquid is, the faster the liquid evaporates. Molecules entering the air still undergo irregular thermal motion: some continue to move upward away from the liquid surface, while others move downward and return to the liquid. Therefore, the difference between the number of molecules escaping from the liquid into the air and the number of molecules moving back from the air into the liquid simultaneously determines the liquid evaporation rate. The higher the air velocity on the liquid surface is, the faster the molecules that escape from the liquid will be carried away by the airflow, resulting in fewer molecules returning from the air to the liquid per unit of time. This is reflected in yet another macroscopic phenomenon: the higher the air velocity on the liquid surface is, the faster the liquid evaporates. As microscopic interpretation is too abstract for junior high school students, only a few students can establish a microscopic model of evaporation, even though teachers apply pictures, molecular models, or multimedia technologies to assist teaching. As students establish a connection between macroscopic phenomena and microscopic nature, they reach a high level of conceptual understanding of evaporation. The expert group thereby determined that a high level of understanding of evaporation means that students can deeply understand the microscopic nature of evaporation and explain how the three factors affect the evaporation rate from a microscopic perspective, as summarized in Fig. 3 below.

IV. THE ASSESSMENT TEST BASED ON THE LEVEL DIVISION

Based on this level division discussed above, a test consisting of 12 single-choice questions (1/4) was designed

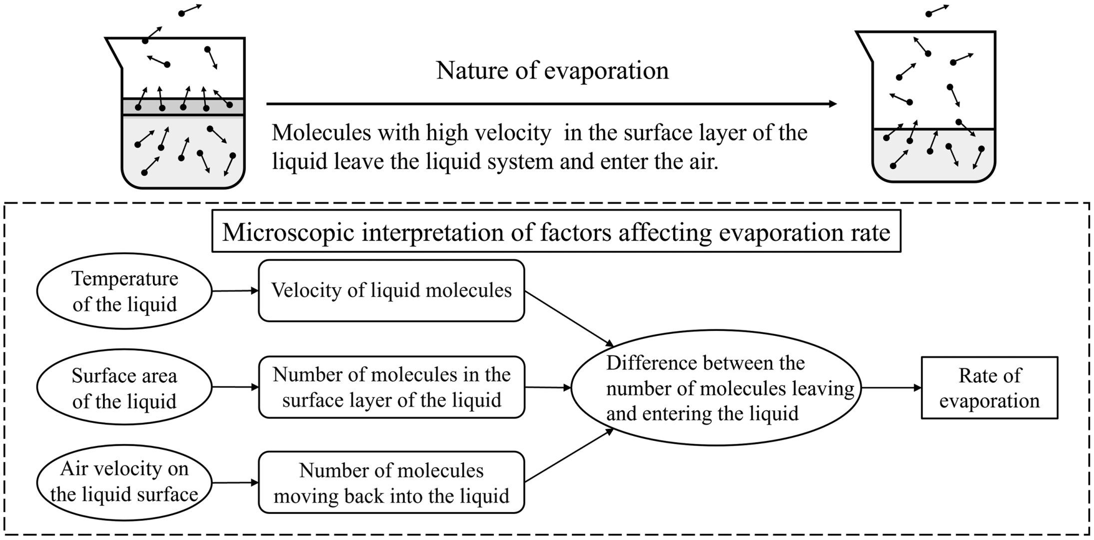


FIG. 3. High level of understanding of evaporation.

to assess students' conceptual understanding of evaporation. All 12 questions were adapted based on the ones that students often encounter in their daily learning and passed the consultation and demonstration with the experts participating in this study. For each question, we attempted to avoid interference from irrelevant information and focused on assessing the corresponding conceptual understanding. These questions can be divided into three sets: simple, preliminary, and integrated, corresponding to the three levels of conceptual understanding of evaporation mentioned above.

The simple set contained four questions (Q1, Q3, Q5, and Q8) that could be solved by mechanically extracting the definition of evaporation. For example, Q3 provided four common phenomena of phase change in daily life and asked students to choose the correct answer, which represented an evaporation phenomenon. Students with the three different levels of conceptual understanding were expected to answer these questions correctly after the evaporation lessons.

The preliminary set contained four questions (Q2, Q6, Q7, and Q10), proposing higher requirements for students' conceptual understanding of evaporation. Students with an intermediate level of understanding of evaporation could answer the questions correctly. For example, Q10 presented four pictures with different evaporation conditions and asked students to predict the volume of water remaining after a certain period. It was expected that students with high and intermediate levels of understanding of evaporation would perform well on these questions, but students with a low level of understanding would have difficulty solving them.

The integrated set contains four questions (Q4, Q9, Q11, and Q12) that could be answered by students with a high level of understanding of evaporation. These questions examined whether students understood the nature of evaporation and whether they could explain the evaporation process from a microscopic perspective. For example, Q12 asked the students to explain the microscopic reason why water evaporates at different rates in beakers of different diameters. It was expected that students with a high level of understanding of evaporation would answer these questions correctly, whereas students with intermediate and low levels of understanding of evaporation would hardly solve them.

The detailed test questions are provided in the Supplemental Material [57]. To assess the reliability of the test, 171 Chinese junior high school students were randomly selected for preliminary testing. The results showed that the Cronbach's alpha of the entire test was 0.886, and the Cronbach's alphas of the three question sets were 0.864, 0.820, and 0.891, respectively, indicating that the test had good structural validity.

V. RESEARCH METHODOLOGY

The participants in this study were 721 seventh-grade students. Before and after the evaporation lesson, all 721 students participated in the pretest and post-test, and some continued to participate in further interviews. Subsequently, various quantitative and qualitative analysis methods were applied to explore the characteristics of the student's conceptual understanding of evaporation, including overview analysis, score change trend analysis, exploratory factor analysis, and thinking process analysis.

A. Participants

Participants were 721 junior high school students from Jinhua, Zhejiang, China. Jinhua is a moderately developed city in China, and the selected school is also a moderately developed school in Jinhua. Therefore, the students' conceptual understanding is representative of the overall level of junior high school students in China to a certain extent. The average age of the students was 12.7 years old, with 371 boys and 350 girls. These participants came from 18 classes. The academic performance between classes was similar, and the contents and strategies of the evaporation lessons adopted by the science teachers of these classes were also similar. Junior high school students in Zhejiang learn an integrated science curriculum, and the topic of this study, evaporation, is to be taught in the seventh grade. In December 2022, 721 students attended a 45-min lesson on evaporation in their own classes. This study was approved by the Zhejiang Normal University Review Board and informed consent was obtained from all participants.

B. Evaporation lesson received by the participants

Evaporation is usually taught in Chinese junior high schools in 45-min lessons. At the beginning of the lesson, the teacher demonstrates the evaporation phenomena in daily life, such as the expansion of a sealed plastic bag containing alcohol. Inspired by these phenomena, students can describe more similar phenomena in life, such as wet clothes slowly drying out in the sun and the water splashed on the ground gradually disappearing. Based on these phenomena, the teacher introduces a scientific definition of evaporation, which is a slow vaporization phenomenon that can occur at any temperature on a liquid surface. To help the students distinguish evaporation from other forms of phase change, the teacher emphasizes the main characteristics of the concept of evaporation to deepen their mechanical memory. The teacher guides the students in estimating the factors affecting the evaporation rate in the designed problem situations. Based on the student's responses, the teacher conducts a series of inquiry experiments through teacher demonstrations and group cooperation. It is not difficult for students to conclude that the temperature of the liquid, surface area of the liquid, and air velocity on the liquid surface are the three main factors that affect the evaporation rate. Finally, the teacher uses models, diagrams, animations, and other methods to simulate the microscopic process of liquid evaporation, increasing the student's understanding of the nature of evaporation. Overall, in the evaporation lesson, teachers not only consider the increase in students' knowledge but also improve students' thinking quality by exploring experiments, model construction, and other ways. After the evaporation lesson, students reach different levels of conceptual understanding of evaporation.

C. Data collection and analysis

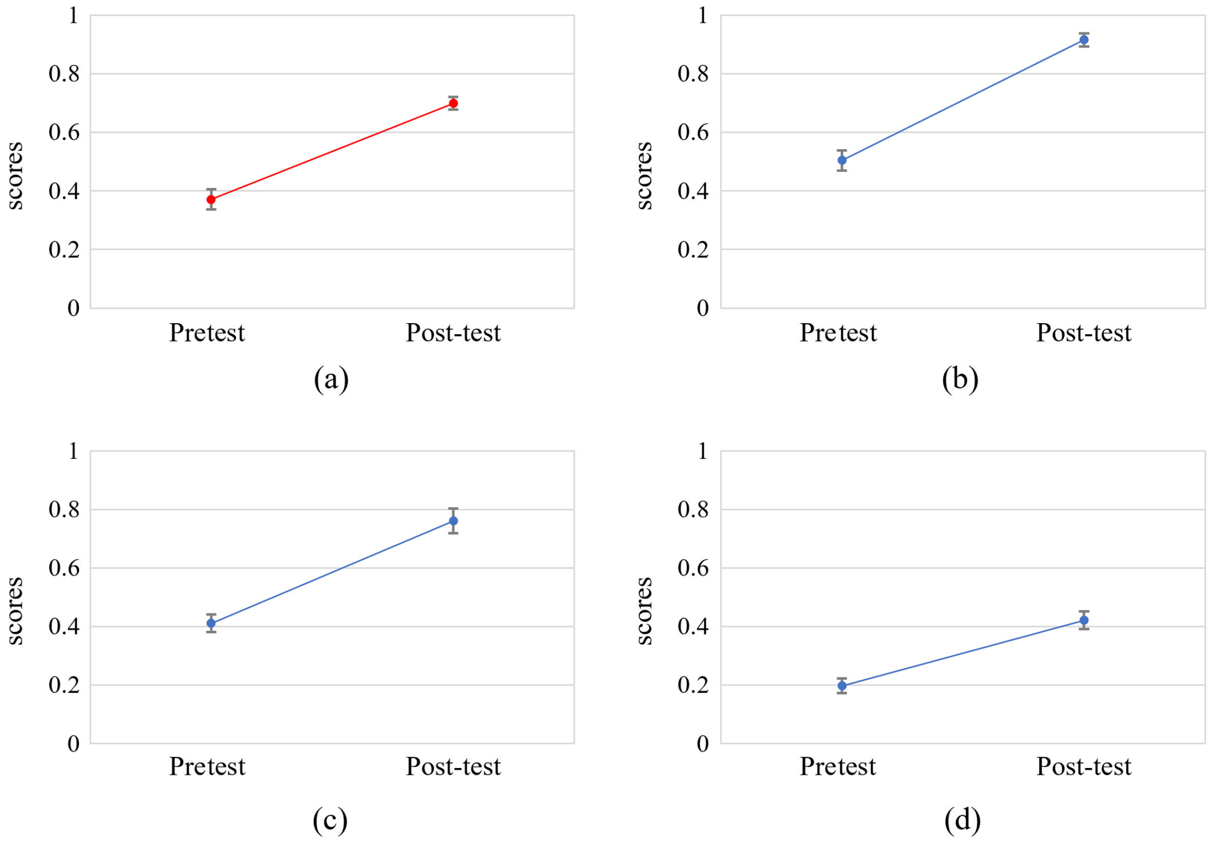
Before and after the evaporation lesson, all 721 students participated in the pretest and post-test. Each test lasted for 30 min. On this basis, 100 students who were randomly selected from the 721 students participated in think-aloud interviews to reveal their thinking process in the problem-solving process so that their conceptual understanding characteristics could be further studied. Each interview lasted approximately 30 min and was audiotaped. During the interview process, some assistants explained the intention of the interview to the interviewees and provided guidance to help them express their problem-solving ideas and thinking processes as clearly as possible. These assistants gained advanced knowledge of the students' possible problem-solving strategies and potential mistakes in answering the questions.

To investigate the characteristics of students' conceptual understanding of evaporation, various quantitative and qualitative analyses of test data and interview results were conducted. Differences between the students' pretest and post-test data were analyzed to examine whether their conceptual understanding of evaporation improved after the evaporation lesson. The score distributions of students with different overall scores on different sets were analyzed to explore the developmental characteristics of students' conceptual understanding of evaporation. Students' post-test performance was further analyzed using exploratory factor analysis (EFA) to explore the structural characteristics of their conceptual understanding. To explore whether students with high total scores had a more integrated understanding of evaporation, an exploratory factor analysis (EFA) was conducted for the students in the top 20%. Moreover, through a qualitative analysis of the interview results, the characteristics of the internal thinking processes of students with different levels of conceptual understanding were revealed as a supplement to the previous quantitative analysis.

VI. RESEARCH RESULTS

A. Improvement of students' conceptual understanding of evaporation

The overall performance of the 721 students in the pretest and post-test is shown in Fig. 4. As shown in Fig. 4(a), there was a significant improvement in the overall performance of the students after receiving the evaporation lesson [0.37 → 0.70, $t(720) = 71.459$, $p < 0.001$,



(a) (b) (c) (d)

FIG. 4. Pretest and post-test performance of students (with error bars denoting standard error). (a) Total. (b) Simple set. (c) Preliminary set. (d) Integrated set.

$d = 1.466$]. However, as shown in Figs. 4(b)–4(d), the degree of improvement varied for each question set. Specifically, the improvement of the simple question set was the most significant [$0.50 \rightarrow 0.92$, $t(720) = 29.248$, $p < 0.001$, $d = 1.263$], followed by the improvement of the preliminary question set [$0.41 \rightarrow 0.76$, $t(720) = 24.703$, $p < 0.001$, $d = 0.993$], and the improvement of the integrated question set was the least [$0.20 \rightarrow 0.42$, $t(720) = 16.224$, $p < 0.001$, $d = 0.802$]. These results indicate, to some extent, that the students' conceptual understanding of evaporation could be divided into three levels. The three-level division was further validated using a subsequent exploratory factor analysis.

B. Structural characteristics of students' conceptual understanding of evaporation

An exploratory factor analysis (EFA) was conducted on the post-test data of all students to obtain more detailed information on their conceptual understanding of evaporation after the evaporation lesson, and the results are shown in Fig. 5. According to Kaiser's rule, all components with eigenvalues greater than 1 should be retained for statistical inference. As shown in Fig. 5(a), three common factors with eigenvalues greater than 1 were extracted, and their variance contributions accounted for 48.715% (27.122%, 11.898%, and 9.692% for factors 1, 2, and 3, respectively). According to the factor loading plot in Fig. 5(b), these three factors corresponded exactly to the three question sets: Factor 1 represents the simple set, factor 2 represents the preliminary set, and factor 3 represents the integrated set. Meanwhile, there was a moderate correlation between students' performance on the simple set and the preliminary set (0.434), while there was a weak correlation between performance on the single set and the integrated set (0.224) and between performance on the preliminary set and the integrated set (0.270). These results further indicate that the level of division of students' conceptual understanding of evaporation in this study was reasonable.

C. Development characteristics of students' conceptual understanding of evaporation

Students were equally divided into five groups according to their total post-test scores. The score distributions of the five groups for the different question sets are plotted in Fig. 6. As shown in Fig. 6, the students who scored in the bottom 20% performed better on the simple question set than on the preliminary and integrated question sets, as predicted. As the total score increased, the scores of students in the next group (20%–40%) in the preliminary questions improved significantly, indicating that these students began to grasp the three major factors that affect the evaporation rate. The improvement in performance on the preliminary questions was still very significant among students with higher total scores (40%–60%), while the scores of the simple and preliminary questions almost reached the highest point. As the total score further increased (60%–80%), students' performance on the simple and preliminary sets only slightly improved, and the scores of the integrated questions increased significantly, indicating that these students have reached a high level of conceptual understanding and could explain evaporation from a microscopic perspective. Students with the highest total scores in the top 20% further increased their score advantage on the integrated questions, achieving high accuracy in each question set. These above results reveal the complete development process of students' conceptual understanding of evaporation, which is consistent with previous theoretical analyses of developmental characteristics. In addition, the item difficulty for each of the three question sets was calculated. The item difficulty of the simple, preliminary, and integrated sets was 0.92, 0.76, and 0.42, respectively. The item difficulties showed that the

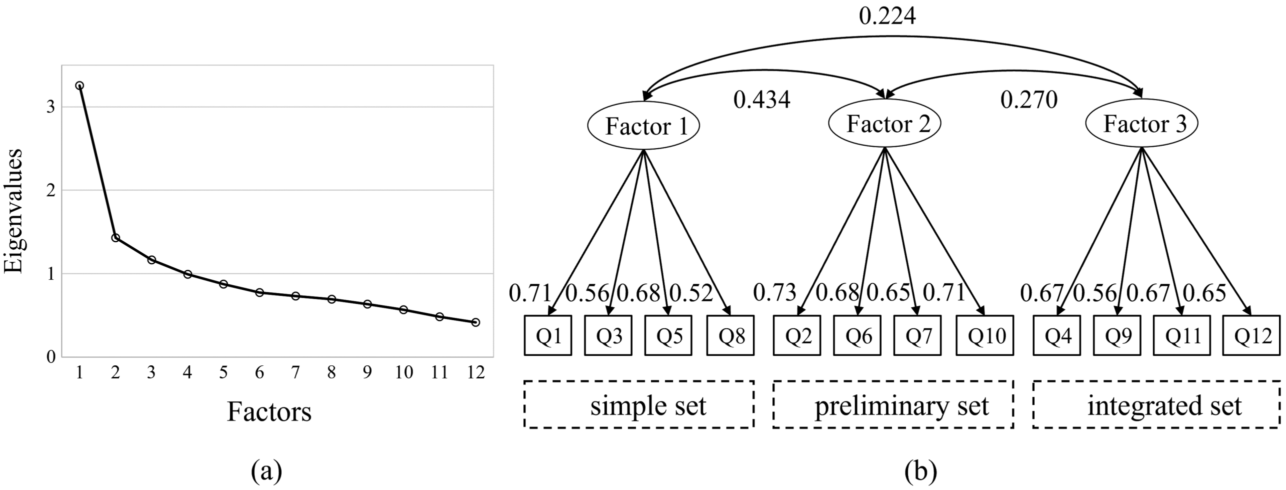


FIG. 5. Factor loadings for EFA of all the 721 students' post-test data. (a) Scree plot. (b) Factor loadings plot.

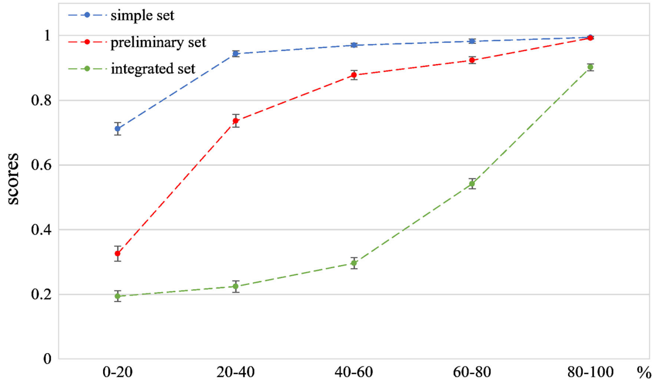


FIG. 6. Score distributions for different question sets of students with different overall performances (with error bars denoting standard error).

simple set should be the easiest for students to answer, and the integrated set should be the hardest. The results strongly support the idea that the development of students' conceptual understanding of evaporation is associated with the transition from the ideas contained in the simple set to those in the integrated set.

D. Structural characteristics of the conceptual understanding of students with high total scores

Exploratory factor analysis was also conducted on the post-test data of the students in the top 20% to reveal the structural characteristics of their conceptual understanding, and the results are shown in Fig. 7. As shown in Fig. 7(a), there was only one common factor with an eigenvalue greater than 1. Its variance contribution is 51.268%, indicating that this single factor could explain most of the information on the original variables, that is, the performance of students with a high level of understanding of evaporation. Compared with the previous EFA analysis, which extracted three common factors, only one factor was extracted in the EFA analysis, which initially suggested that the students in the top 20% had a more integrated understanding of evaporation. According to the factor loading plot in Fig. 7(b), there was a moderate or strong correlation between the students' performance on each question and the common factor, further demonstrating the integrity of their conceptual understanding. Since these students answered almost all the questions correctly, the results of the EFA need to be supplemented by further qualitative analysis.

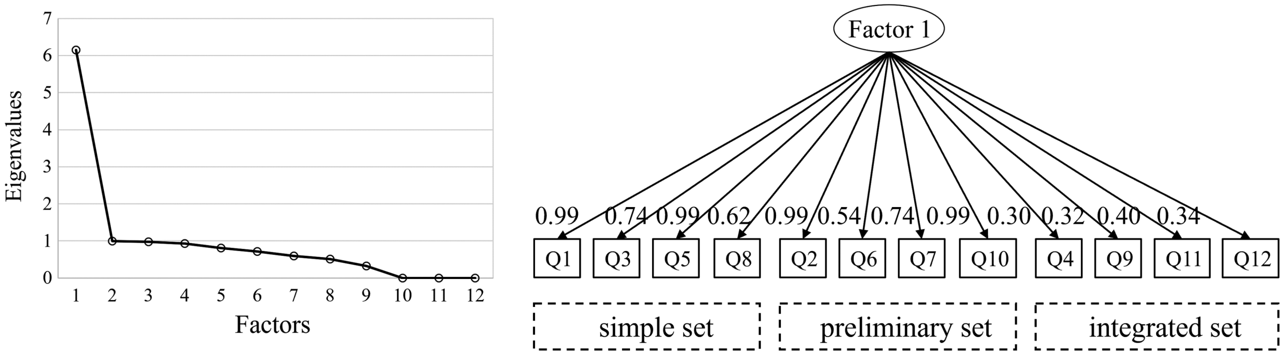
E. Students' conceptual understanding of evaporation reflected by their thinking process

To identify students' thinking processes and conceptual understanding of evaporation, 100 students were randomly selected from the 721 students to participate in think-aloud interviews. One hundred students were asked to explain in detail how they arrived at their answers. Based on the students' thinking processes and the previous division, their conceptual understanding of evaporation can be divided into three levels, as described below.

Low level: Students with a low level of understanding of evaporation could only mechanically memorize the definition of evaporation and then identify evaporation phenomena in life according to their life experiences. In other words, the students' strategies for solving evaporation-related problems largely depended on memorization and life experiences. However, even if they had relevant experience with the changes in the evaporation rate, they could not systematically account for such changes. For example, students A and B scored well on simple questions through mechanical matching, but their scores significantly decreased significantly on preliminary and integrated questions.

Student A: (For question 2) I know that water evaporates during the drying process of wet clothes, and I also have the experience that spreading out my clothes can make them dry faster, but I am not clear about the cause.

Student B: (For question 10) This question asks which container has the least amount of water in it after a period of time, that is, in which



(a) (b)

FIG. 7. Factor loadings for EFA of students with high total scores. (a) Scree plot. (b) Factor loadings plot.

container the water evaporates the most. After comparing the four options, I intuitively believe that the operation of B, C, and D will all change the amount of water evaporated, but I am not sure how and why it changes.

Intermediate level: Students with an intermediate level of understanding of evaporation not only grasped the definition of evaporation more accurately than students with a low level of understanding but also connected their life experiences with the three major factors that affect the evaporation rate. However, they could only explain changes in the evaporation rate at the macroscopic level, and at the microscopic level, and their ignorance is exposed. For instance, students C and D performed similarly to the students with a high level of understanding of evaporation on the simple and preliminary sets but did not perform as well on the integrated questions.

Student C: (For question 6) Blowing air on the surface of a water drop can accelerate the evaporation of the water drop b, as it increases the air velocity on the liquid surface. (For question 11) I just have a rough idea that the number of molecules returning from the air to the liquid during the evaporation process is related to the evaporation rate, and the operations in the options are also related to the evaporation rate. Maybe the key to solving the problem is here, but the problem is too difficult for me.

Student D: (For question 7) The evaporation rate in the beaker c is the slowest, and the evaporation rate is positively correlated with temperature, so it is obvious that the water temperature in the beaker c is the lowest. (For question 4) I can tell that the four choices are all scientific descriptions of water molecules, but if I have to choose the one that is not related to evaporation, I can only exclude option D, while the other three options are probably the correct answer.

High level: The salient feature of students with a high level of understanding of evaporation was their understanding of the nature of evaporation. The evaporation process at the microscopic level provides a more essential perspective for students' conceptual understanding, and the knowledge elements related to evaporation are no longer fragmented but are more closely connected through the nature of evaporation. Taking the performances of students E and F as examples, they were able to solve the majority of the questions in each set.

Student E: (For question 9) Choosing the correct answer is not difficult because heating can accelerate molecular motion, but I still checked other options to ensure that changing the temperature would not change these factors. (For question 11) I mainly swayed between option B and option D, but when I imagined the molecules above the liquid surface being blown away by the airflow, I got the correct answer, D.

Student F: (For question 4) Water is composed of constantly moving water molecules, among which the faster moving molecules can jump into the air. I recalled the microscopic process of water evaporation like this and used the exclusion to choose C. (For question 12) Using a beaker with a larger diameter will only change the number of molecules in the surface layer, so I think the answer is D.

TABLE I. Number of students at each level among the 100 students interviewed and the interviewees' average scores on each question set.

Level of conceptual understanding	Total	Simple set	Preliminary set	Integrated set
Low (35)	0.41	0.69	0.34	0.20
Intermediate (42)	0.65	0.88	0.75	0.33
High (23)	0.94	0.99	0.93	0.89

The distribution of the level of conceptual understanding and average performance on the post-test of the 100 interviewed students is shown in Table I. Among these students, the number of students with low, intermediate, and high levels of understanding was 35, 42, and 23, respectively. Students' performance at each level of understanding in the different question sets was consistent with the results of the previous quantitative analysis.

VII. CONCLUSIONS

Consistent with previous studies of conceptual understanding [47–52], this study explored the development process of students' conceptual understanding of evaporation. Through a literature review, analysis of China's Compulsory Education Science Curriculum Standards, and expert consultation, this study divided students' conceptual understanding of evaporation into three levels—low, intermediate, and high—and presented the cognitive characteristics and problem-solving performances of students with different levels of conceptual understanding. Based on the level division, a set of test questions was developed and implemented to evaluate Chinese seventh-grade students' conceptual understanding of evaporation. The implementation results confirmed the rationality of the level division and the effectiveness of the test questions.

Students with a low level of conceptual understanding struggled with most questions. They mechanically memorized the definition of evaporation and could identify evaporation phenomena based on the memorized examples. However, their recognition relied more on mechanical matching than on scientific reasoning, which requires a deeper understanding.

Students with an intermediate level of conceptual understanding were able to answer most of the questions, but their learning was not completely free from rote. The most important and difficult knowledge element related to evaporation is its microscopic nature. These students could not understand the concept of evaporation from a microscopic perspective, which resulted in incoherent reasoning.

Students with a high level of conceptual understanding were able to answer almost all questions. They developed a microscopic model of evaporation that could be flexibly applied to the explanation of phenomena and to conduct scientific reasoning and problem solving. Their conceptual understanding of evaporation also deepened their understanding of other forms of phase change, such as condensation and liquefaction. In addition, the conceptual understanding of these students is still developing. The high level defined in this study is not the ultimate level of students' conceptual understanding of evaporation.

The problem-solving behaviors of students at different levels reveal a progression of their conceptual understanding of evaporation, which develops from the accumulation of relevant factual experience to the exploration of influencing factors, and finally to the explanation of its microscopic nature. Through the progression of conceptual understanding, students demonstrate greater accuracy, higher proficiency, and more coherent reasoning in problem solving. All of these are indications that students are approaching a higher level of conceptual understanding and problem solving.

Consistent with the findings of previous studies on scientific concept learning, the crucial role of grasping the nature of concepts in conceptual understanding was revealed [47–52]. For the concept of evaporation, the most important and difficult knowledge is the nature of evaporation: the molecules in the surface layer of a liquid leave the liquid system and enter the air. The microscopic nature of evaporation can be applied to explain the macroscopic phenomenon and the factors influencing the evaporation rate, helping students understand evaporation at a deeper level. Thus, emphasizing the nature of concepts may be an essential instructional strategy for improving students' conceptual understanding. In practice, targeted intervention suggestions can be provided to students with different conceptual understanding levels of evaporation.

In conclusion, this study extends previous work on assessing students' conceptual understanding of evaporation and illustrates the development mechanism of students' conceptual understanding of evaporation. The results of this study provide both theoretical and practical references for future research on conceptual understanding. It should be pointed out objectively that this study still has a few limitations. First, this study was conducted with Chinese junior high school students, so the generalizability of the findings to other educational contexts requires further validation. Second, evaporation is a difficult concept for junior high school students to understand. Therefore, it is necessary to develop more assessment approaches from other perspectives to study the conceptual understanding of evaporation.

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