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ONE HUNDRED CORE CONCEPTS IN CHEMISTRY AND UPPER-SECONDARY SCHOOL TEACHERS' AND STUDENTS' CHEMISTRY CONCEPTUAL STRUCTURES

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Abstract. *A solid grasp of basic concepts and their relationships can stimulate learning motivation, improve teaching quality, and help students to build a body of knowledge in a discipline. Most of the previous studies have considered one chemistry topic amongst many others. To date, no studies have been conducted to explore the conceptual structures of teachers and students based on chemical concepts. Experts, teachers, and students (N=2348) from three public universities and ten upper-secondary schools in China participated in the studies. In Study 1, personal interviews, material evaluation, and importance rating questionnaires were conducted to determine the core concepts. In Study 2, the multidimensional scaling (MDS) and cluster analysis (CA) were conducted to explore the conceptual structures of upper-secondary school teachers and students. Then the structural differences between high- and low-achieving students were compared. The results showed that the three-dimensional solutions were appropriate for the conceptual structures of teachers and students, respectively. The high-achieving students have a more scientific and organized conceptual structure than those of low-achieving students. This study is the first to explore core concepts and their structure with a large sample size, and the reliable results help students understand abstract chemical concepts and improve their interest in scientific disciplines in the future.*

Keywords: *conceptual structure, core concepts in chemistry, multidimensional scaling, cluster analysis, upper-secondary school students*

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Introduction

Concepts are the foundation of human knowledge structures (Johnson et al., 1994), which have been the center of attention in linguistic psychology (Taber, 2013). In recent years, conceptual research has received increasing attention in education.

Drawing from Bruner's structure curriculum theory, students' construction and possession of an organized discipline knowledge system is an essential aim of science education, including chemistry (Bruner, 1964). Prior to this, students were required to obtain an understanding of the basic chemistry concepts and principles (Bruner, 1964; Pinar, 2004). Many studies have suggested that a lack of understanding of chemical concepts impedes students' abilities to solve chemical problems and damages the integrity power of the whole conceptual structure (Burrows & Reid Mooring, 2014; Wang & Barrow, 2013). However, as these discipline concepts are not part of our daily lives, students do not have sufficient preconceptions to make connections with these abstract and complicated concepts. Thus, it is challenging for students to assimilate new concepts into their minds to establish connections with their existing conceptual structure (Joki et al., 2015). As one of the Science, Technology, Engineering, and Math (STEM) disciplines, chemistry contains many basic abstract concepts that are essential for the body of knowledge. Therefore, exploring chemical concepts and understanding their relationships is crucial.

Many new concepts have emerged during the development of Chemistry and the reform of curriculum standards, which indicates the importance of exploring chemical concepts and the structure of chemistry (Apriwanda et al., 2021; Treagust et al., 2000). Specifically, chemistry has evolved from macroscope to microscope levels, from simple to complex molecules, from

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static to dynamic perspectives, and from one single discipline to inter-discipline. During this transition, students and teachers update their concepts, reorganizing them as new concepts. For instance, inductive effect and refuse classification emerged in the new chemistry textbooks. Besides, China releases the revised version of Chemistry Curriculum Standards for Compulsory Education in 2022. Implementation of these standards indicates the accomplishment of the construction of chemistry knowledge based on the big ideas and core concepts. These standards also stressed the importance of developing students' integrated understanding of the big ideas and core concepts in scientific literacy (Stern & Roseman, 2004).

Considering the importance of understanding concepts for chemistry learning, it is necessary to determine core concepts and explore their structure in the context of disciplinary development reforms. Since core concepts are the most important part of the concepts pool, chemistry teachers can use these core concepts as a general reference and implement them in future teaching process.

For the conceptual structure representation, multidimensional scaling (MDS) has been widely used due to its simplicity and scientific objectivity. This method visualizes the representation of the global relationships among concepts through the participants' categorical data of concepts (Arce et al., 2010; Mai et al., 2021). The specific steps of this method are listed as follows: (a) classifying concepts, getting distance data, and resenting these distance data as relationships among research objects in a multidimensional space; (b) obtaining the fit indexes, spatial coordinates, and the distribution map of each dimension solution; and (c) determining the optimal dimension solution by the fit indexes, then analyzing the distribution map of the optimal dimension (Gordon & Hayward, 1973).

Although the distance data obtained from the participants' classification of concepts are objective, the transformation from data into a distribution map and the judgement of the conceptual structure based on the distribution map is subjective and is affected by knowledge, experience, or cognitive ability. In other words, individuals with abundant chemical knowledge or a high level of cognitive ability are able to summarize the commonalities of some concepts in the map well and are not confused by the misclassification of a concept in the map. Therefore, further stacking using cluster analysis (CA) methods is needed to make the classification results more objective and precise (Mai et al., 2021; Qian et al., 2009). The dimensional coordinates of each concept can be obtained using CA, which significantly reduces the difficulty or inconsistency of clustering according to the spatial distribution map (Huang & Qian., 2020).

To date, a handful of studies have explored concrete chemical concepts in some topics, such as acid-base balance structure (Wilson, 1998), chemical equilibrium (Mai et al., 2021), and organic chemistry (Hrin et al., 2018). However, no study was conducted to explore the core concepts and conceptual structures of upper-secondary teachers and students in the field of chemistry discipline but not only in one specific topic. This study aims to address this gap.

According to the previous discussion, the present research aims to answer three questions:

Q1. What are the core concepts in the perception of chemistry by teachers and students?

Q2. What are the features of conceptual structures in chemistry for teachers and students?

Q3. Are there any differences in conceptual structures in chemistry between high- and low-achieving students?

Research Methodology

General Background

Two studies were conducted to determine the chemistry core concepts and teachers' and students' conceptual structures. In Study 1, the core concepts were determined by personal interviews, material evaluation, and an importance rating questionnaire.

In Study 2, MDS and CA methods were used to explore the conceptual structures in upper-secondary school teachers and students. First, a free classification analysis was used to classify the core concepts by teachers and students. Then MDS analysis was then performed using the free classification data to determine the structural dimensions of these core concepts. Second, the CA was conducted to obtain the multidimensional representations data, which were analyzed to classify the core concepts. Finally, the differences in the conceptual structures between high- and low-achieving students were compared.

Overall, the results of the present studies would contribute to the establishment of the chemistry core concepts and provide suggestions for the design of chemistry teaching materials—a theoretical basis and practical guidance under the background of the new chemistry curriculum reform in China.

Participants

Two thousand four hundred experts, teachers, and students from three public universities and ten upper-secondary schools in nine areas of China were selected by convenient sampling. Excluding 52 invalid questionnaires (efficient rate=93.92%), the final sample of participants was 2348. Table 1 shows the distribution and subjects in the two studies (see below for the description of the Instrument and Procedures).

Table 1
Demographic Characteristics of Participants

Study	Group	*n*
Study 1	Group 1. Chemistry experts and chemical educators	12
	Group 2. Undergraduates (55) and postgraduates (31)	86
	Group 3. Upper-secondary chemistry teachers	405
	Group 4. 12th-grade upper-secondary school students	1109
Study 2	Group 5. Upper-secondary chemistry teachers	346
	Group 6. High-achieving students in chemistry	197
	Group 7. Low-achieving students in chemistry	193
Total valid participants (*N*)		2348

Instrument and Procedures (Study 1)

Study 1 had two steps, concept extraction and concept selecting. The first step includes personal interviews and material evaluation; the second step refined the concepts extracted in the first step through an importance rating questionnaire (processes are shown in Figure 1).

For one-to-one interview, the chemists and chemical educators were interviewed separately. Interviewees were informed in advance of the time, place, and topics of the interview.

We adopted a semi-interview that contained three questions:

1. From the perspective of the development of chemistry, what are the core concepts? (Major question).
2. What is your main research field? (Minor question).
3. What are the concepts in frontiers of contemporary Chemistry?" (Minor question).
4. All interview records were transcribed into texts. Repetitive concepts were removed and summarized in an Excel sheet.

In addition to the interview, material evaluations were conducted to extract the concepts. Eighty-six undergraduate and postgraduate students, majoring in Subject Teaching (Chemistry) and Chemistry Curriculum and Pedagogy, were engaged in material evaluation. These materials stem from three parts: chemistry tests in the college entrance examination, the chemistry curriculum standards, and upper-secondary school chemistry textbooks, all covering concepts in the upper-secondary school chemistry curriculum. Students were asked to summarize the concepts appeal in the materials in Excel sheet and count the frequency of occurrence of each concept.

After combining two parts of chemical concepts and removing repetitions, the rest were randomly arranged to form an importance rating questionnaire. Frontline chemistry teachers and 12th-grade students were asked to assess the importance of each concept on a 7-point Likert scale (1=least important, 7=extremely important). For these participants, the frontline teachers were all in-service teachers with more than one year of teaching experience; the 12th grade students had taken the elective chemistry course and reviewed the chemistry knowledge in the first round of review at upper-secondary school, so the structure of chemistry knowledge was formed in their perceptions. The higher the score of each concept, the more important the concept is in the upper-secondary school chemistry curriculum. Finally, the concepts with high scores were selected as the core concept.

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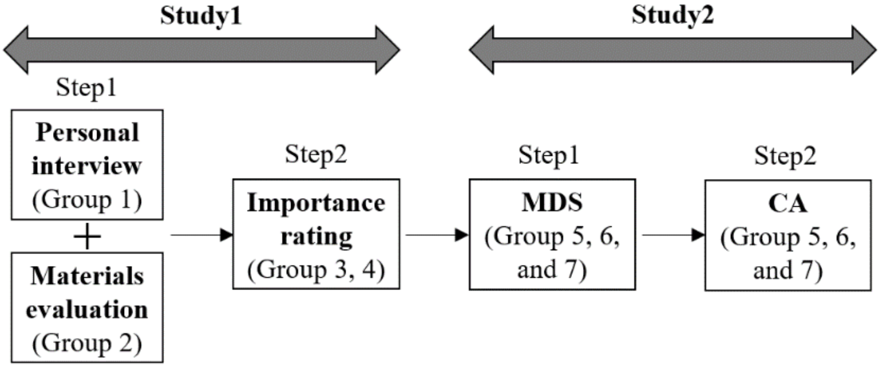
Figure 1
Instrument and Procedures (Study 2)



The one hundred core concepts were formed in Study 1 and their structure further validated in Study 2, which also had two steps. Before Study 2, the top 25% and bottom 25% of students were identified based on their chemistry scores in the college entrance examination (the first mock chemistry examination) and defined two groups as high- and low-achieving students, respectively.

In step 1, upper-secondary school chemistry teachers and two group students were asked to freely classify the 100 core concepts in a paper questionnaire. Classification data were manually entered into digital data. The entering process was completed in approximately three months. The digital data were superimposed to a dissimilarity matrix of 100×100 by the Style program. Following the rules, the matrix intersection of the concepts in the same category is marked as 0 and marked as 1 otherwise. The classification data of all participants were imported into SPSS software. The organization structure was explored using MDS. The fit indexes of each dimension and the spatial coordinate of each core concepts were obtained.

The optimal dimension was selected by fit indexes. The spatial coordinates were used for the cluster analysis (CA) in step 2. Finally, the differences in the conceptual structures between high- and low-achieving students were compared.

Data Analysis

The preliminary analysis (mean scores and standard deviations) of each core concept, MDS, and CA were conducted using IBM SPSS (version 25, USA).

Research Results

Study 1

The interviews of chemists and chemical educators revealed that the concepts they mentioned are broad and forefront. There are classic chemical concepts (e.g., molecule), cutting-edge interdisciplinary concepts (e.g., nano-structure), and practice technical concepts (e.g., simulation experiment). After excluding the repetition, 167 concepts were finally listed. For evaluating materials, three parts of materials were combined before excluding the repetition, and finally ended up with 214 concepts.

After combining two parts of chemical concepts, removing repetitions, and keeping the rest in random order, an importance rating questionnaire was formed. Using the SPSS, the mean score of the importance of each concept ranges from 2.15 to 6.42. Using the median score (i.e., 4) of the importance of concepts as the selection criterion, 96 concepts with an importance score of 4 or higher were selected out. Additionally, with reference to chemistry textbooks and the opinions of chemists and school teachers, four concepts were added as concepts because of their high frequency in China's college entrance examination after removing the concepts of college chemistry: rustiness (3.94), slow oxidation (3.93), chemical energy (3.92) and alloy (3.69), which were added as concepts with an average importance score close to four. Finally, 100 chemical concepts were selected just right (see Table 2).

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Table 2
The One Hundred Core Concepts in Chemistry

n	Core Concepts	*M*	n	Core Concepts	*M*	n	Core Concepts	*M*	n	Core Concepts	*M*
1	periodic table	6.42	26	mass fraction of the solute	5.60	51	molecule	5.28	76	homologue	4.71
2	law of conservation of mass	6.42	27	reduction	5.58	52	electron transfer	5.26	77	saturated hydrocarbon	4.69
3	periodic law of elements	6.40	28	ionization equilibrium	5.57	53	isotope	5.20	78	combustion	4.67
4	redox reaction	6.33	29	electrolyte	5.56	54	nuclear charge	5.20	79	proton	4.66
5	chemical equation	6.29	30	ion reaction	5.56	55	decomposition reaction	5.19	80	organic reaction	4.58
6	amount of substance	6.27	31	double replacement reaction	5.55	56	electrolysis	5.17	81	atomic nucleus	4.51
7	mole	6.22	32	solution	5.55	57	functional group	5.14	82	green chemistry	4.43
8	molarity	6.21	33	neutralization reaction	5.53	58	ionic bond	5.13	83	voltaic cell	4.43
9	molar mass	6.16	34	compound	5.50	59	chemical bond	5.08	84	weak electrolyte	4.37
10	pH	6.06	35	ionization	5.48	60	composition	5.02	85	compose	4.35
11	chemical property	6.03	36	atom	5.47	61	organic compound	4.99	86	saponification reaction	4.31
12	elemental symbol	5.91	37	acid-base indicator	5.43	62	material structure	4.98	87	atomic group	4.29
13	ionic equation	5.88	38	saturated solution	5.42	63	rates of reaction	4.95	88	acid rain	4.28
14	relative atomic mass	5.80	39	atomic structure	5.42	64	covalent bond	4.95	89	Tyndall effect	4.28
15	element	5.80	40	substance property	5.42	65	catalyst	4.91	90	particle	4.22
16	chemical reaction	5.78	41	element	5.80	66	noble-gas configuration	4.90	91	chemical battery	4.20
17	configuration of extra-nuclear electron	5.73	42	hydroxide	5.40	67	average molecular weight	4.86	92	greenhouse effect	4.15
18	valence	5.71	43	electron	5.36	68	valence state	4.84	93	crystallization	4.15
19	chemical formula	5.69	44	isomerism	5.34	69	solute	4.80	94	energy	4.07
20	single displacement reaction	5.67	45	hydrolysis	5.34	70	flame test	4.78	95	colloid	4.06
21	pure substance	5.65	46	ion	5.33	71	physical change	4.76	96	crystal	4.01
22	acid, alkali, and salt	5.63	47	oxide	5.31	72	mixture	4.74	97	rustiness	3.94
23	combination reaction	5.63	48	solubility	5.31	73	peroxide	4.74	98	slow oxidation	3.93
24	atomic number	5.63	49	substitution reaction	5.29	74	classification of substances	4.73	99	chemical energy	3.92
25	chemical equilibrium	5.62	50	addition reaction	5.29	75	solvent	4.73	100	alloy	3.69

Note: M refers to the mean scores of all concepts.

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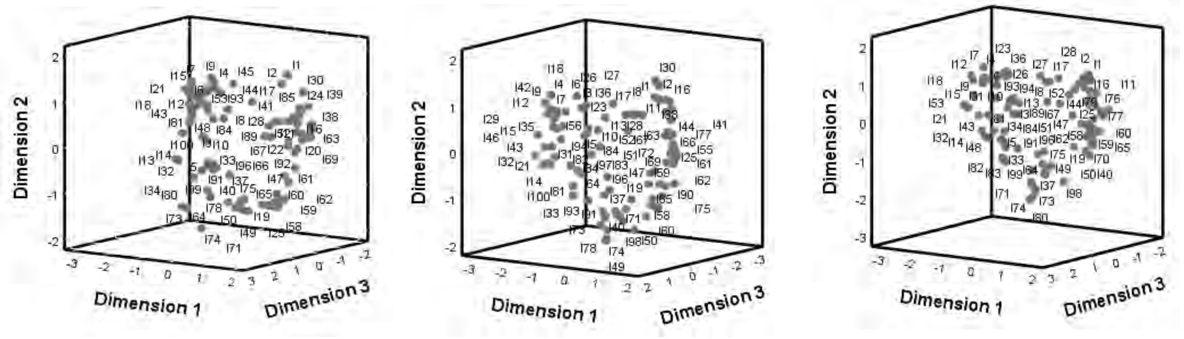
Study 2

The optimally fitting model was selected on the basis of indexes of Stress and RSQ. Stress values between 0.05 and 0.10, and RSQ values close to 1 indicate acceptable fits (Borg & Groenen, 2006). The results shown that the fit indices of three-dimensional solutions are appropriate for the conceptual structures of both teachers and students (see Figure 1), Stress=0.09 and RSQ=0.95 for teachers, Stress=0.09 and RSQ=0.96 for high-achieving students, with Stress=0.08 and RSQ=0.97 for low-achieving students. That is, the three-dimensional models are able to explain the data.

Figure 2

Three-dimensional Representation of the Conceptual Structure



(a) Teachers (b) High-achieving students (c) Low-achieving students

Note: Dimension 1 denotes reactive and material conceptual attributes; Dimension 2 denotes relational and structural conceptual attributes; Dimension 3 denotes fundamental and applied conceptual attributes, same below.

In addition to the support of the above fitting data, the intuitive results of three groups (teachers, high- and low-achieving students) displayed by two-dimensional mapping images also reveal that the three-dimensional structure is a good reflection of the basic characteristics of chemistry (see Figures 3, 4, and 5).

In Study 2, Dimension 1 reflects the shift from reactive to material structural attributes (from left to right, see Figures 3a, 3c, 4a, 4c, 5a, and 5c). The former includes concepts such as ion reaction, chemical equilibrium, and hydrolysis, etc., which are characterized by the dynamics of chemical reactions; the latter includes static concepts such as pure substance, mixture, and isotope, etc., which are related to the laws of substances. Dimension 2 reflects the shift from relational to structural conceptual attributes (from left to right, see Figure 3b, 4b, and 5b; from bottom to top, see Figure 3a, 4a, and 5a). The former includes concepts related to chemical structures such as solute and crystal; the latter includes the law of conservation of mass and periodic law of elements and some other concepts about the relationship between substances. Dimension 3 reflects the shift from fundamental to applied conceptual attributes (from top to bottom, see Figure 3b, 4b, and 5b; from bottom to top, see Figure 3c, 4c, and 5c). The former includes concepts related to daily or scientific research application, such as the greenhouse effect and acid rain; the latter includes concepts related to basic chemistry, such as molecules and ions. It can be seen visually in these figures that high-achieving students' classification is more concentrated compared to low-achieving students. That is, high-achieving students are better able to establish inter-concept relationships based on their understanding of concepts when classifying them.

In general, all three dimensions of spatial distribution for teachers and students reflected the characteristics of the chemistry discipline. However, the axis naming was based on the researcher's knowledge, experience, and cognitive ability, that is, experienced and cognitively competent researchers were able to summarize the characteristic commonalities of concepts based on their distribution in the coordinate axes. Therefore, the CA methods based on the three-dimensional coordinates were applied to make the classification clear and precise.

Figure 3

Two-Dimensional Projections of the Three-Dimensional Solution by Teachers.

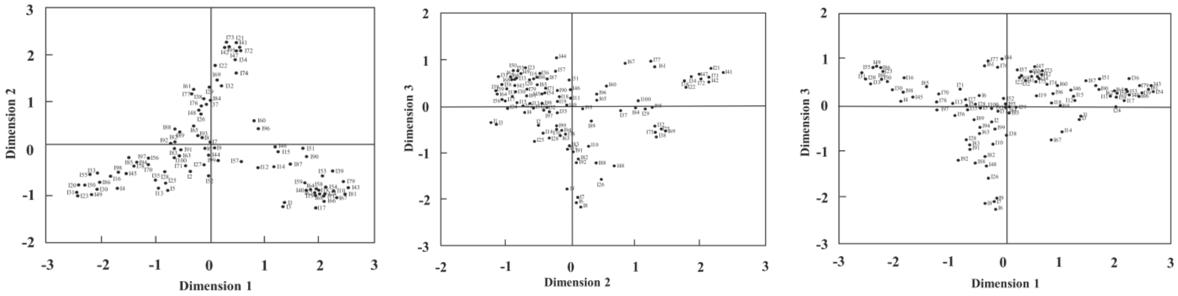


Figure 3a

Figure 3b

Figure 3c

Figure 4

Two-Dimensional Projections of the Three-Dimensional Solution by High-Achieving Students.

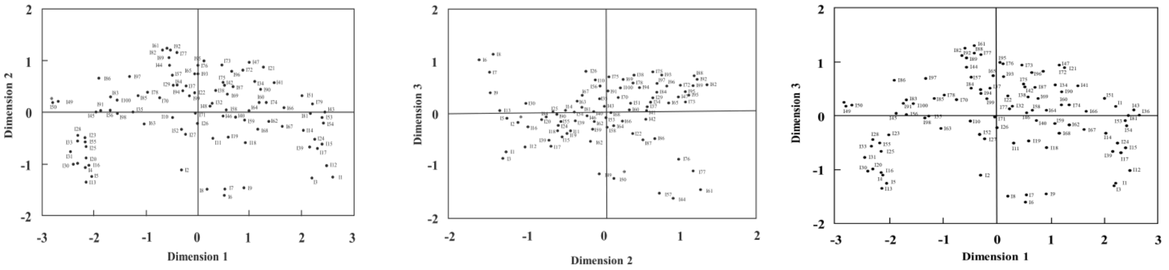


Figure 4a

Figure 4b

Figure 4c

Figure 5

Two-Dimensional Projections of the Three-Dimensional Solution by Low-Achieving Students.

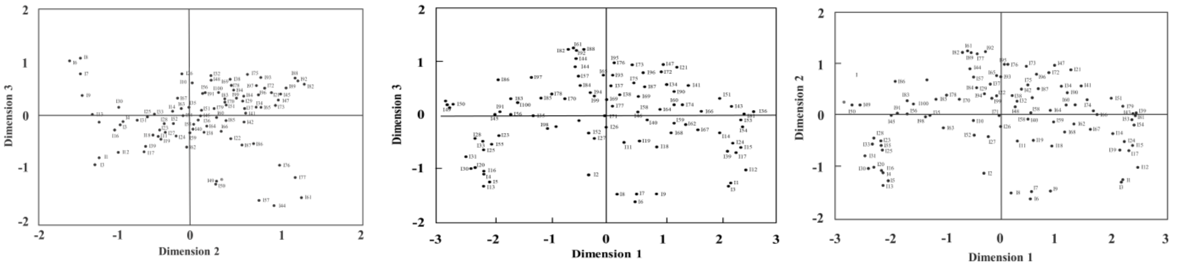


Figure 5a

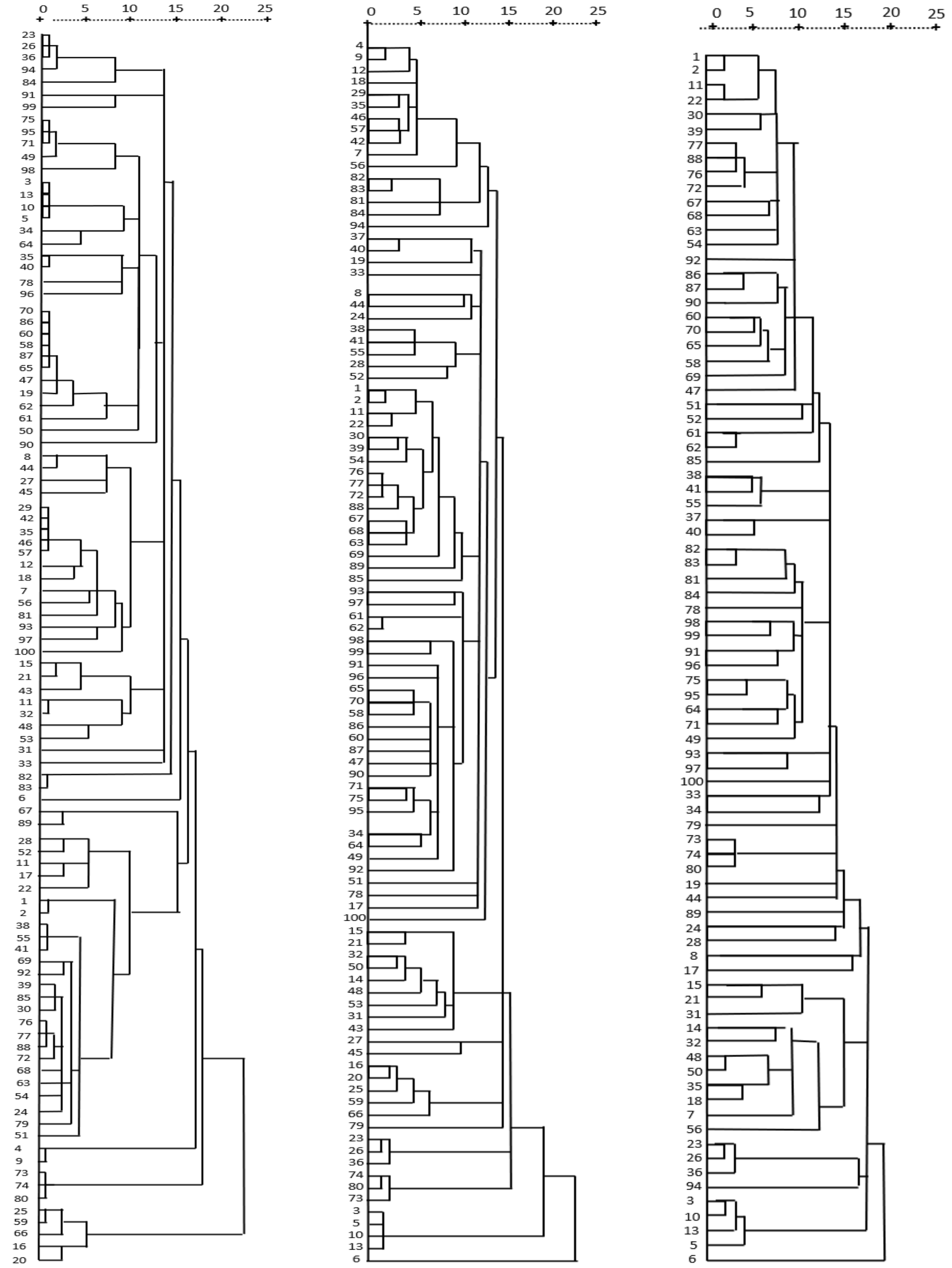
Figure 5b

Figure 5c

The dendrograms of CA results are shown in Figure 6. The measure ruler of the clustering dendrogram (see the top of Figure 6) indicates the adjustment distance of each concept in clustering. The concepts can be classified into different categories by choosing different scale criterion. To show the results more visually, we clustered the concepts of teachers using "14" as the scale criterion and high- and low-achieving students into 10, 9, and 8 clusters, respectively.

Figure 6

The Dendrograms Obtained by Hierarchical Cluster Analysis of Different Groups.



(a) Teachers (b) High-achieving students (c) Low-achieving students

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Table 3
The Classifications Obtained by Cluster Analysis

Clusters of teachers	Clusters of high-achieving students	Clusters of low-achieving students
1. Microcosmic	1. The law of conservation of mass	1. The law of conservation of mass
2. Classifications of substances	2. Concepts related to the amount of substance	2. Concepts related to the amount of substance
3. Chemical terms	3. Chemical application	3. Organic reaction
4. The law of conservation of mass	4. Organic reaction	4. Chemical reaction
5. Organic concepts	5. Organic concepts	5. Organic concepts
6. Organic reaction	**6. Concepts of redox reactions**	**6. Reduction**
7. Chemical amounts	7. Electrochemistry and equilibrium	7. Electrochemistry and equilibrium
8. Chemical application	8. Others	8. Others
9. Energy	9. Chemical reaction	
10. Physical phenomenon		

Note: Concepts in bold indicate that they are unique to the group.

The concepts within each cluster of teachers and students were further analyzed. It was found that the first and second clusters (i.e., microcosmic and classification of substances) of teachers contain many concepts within them, which could be further classified into sub-clusters. The first cluster contains five sub-clusters: 1) chemical characterization, 2) the periodic table of elements, 3) chemical bonds, 4) microcosmic structure, and 5) microcosmic concepts. The second cluster contains seven clusters: 1) concepts of solution, 2) stoichiometry, 3) classifications of substances, 4) chemical properties, 5) chemical reactions, 6) applications of chemical reactions, and 7) principles of chemical reactions and electrochemistry. The teachers' conceptual structure begins with "classifications of substances" and sequentially ties together with "chemical property", "reaction", and "application" to form the categories 2. In general, the teachers' classification was relatively complete and scientific.

On the other hand, the clustering results of the high- and low- achieving students showed that the eighth clusters (i.e., others) contain many concepts within them, which could be further classified into nine sub-clusters and ten sub-clusters, respectively. For high-achieving students, the sub-clusters included 1) concepts of electrolytes, 2) basic concepts, 3) chemical bonds and valence, 4) concepts of microcosmic structure, 5) classifications and properties of substances, 6) ions, g) acid-base indicator, 7) chemical formula, and 8) rustiness. For low-achieving students, the sub-clusters included 1) microcosmic and classifications of substances, 2) chemical bonds, 3) electrolyte, 4) solution and energy, 5) physical change, 6) rustiness, 7) chemical calculation, 8) atomic group, 9) chemical application, 10) acid alkali salt, 11) substance properties, l2) average molecular weight, 13) structure, 14) chemical characterization.

We found several common and different features between the two student groups' conceptual structures. Regarding the common features, since some concepts, such as atomic clusters, are not found in chemistry textbooks and exams, both groups did not classify them properly. That is, high-achieving students classified "atomic clusters" in category 4 (i.e., organic), but low-achieving students classified it in the category 8 (i.e., others); whereas the teachers classified it into the category 1 (i.e., microcosmic). Although both groups of students mixed many subcategories in category 8 (i.e., others), there were still some differences between the high- and low-achieving students. For example, the high-achieving students, in agreement with the teachers, classified "chemical application" separately, indicating that they had a better understanding of categorizing the concepts, such as acid rain, green chemistry, and the greenhouse effect while low-achieving students classified them as "others". Another example is that high-achieving students combined their middle and high chemical knowledge and grouped "acid, alkali, and salt" with "electrolytes" together, while the low-achieving students grouped them separately.

In general, the conceptual structure differed significantly between high- and low-achieving students. Low-achieving students tended to classify concepts based on recent learning, and some concepts that had been learned too long ago were often classified separately and conceptualized confusingly. This indicates that low-achieving students' conceptual structure in chemistry is incomplete, and the classification of concepts is confusing.

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Discussion

After determining the core concept in chemistry through personal interviews, material evaluation, and importance rating questionnaire, this research investigated the conceptual structures of upper-secondary school teachers and students by using MDS and CA method, then further compared the differences in their conceptual structures of chemical concept. Two parts of the results were discussed as follows.

The quality of core concepts

The results of Study 1 showed that the data sources for the selection of core concepts are diverse and that the one hundred core concepts comprehensively cover the "basic structure" of the discipline of chemistry.

The basic structure of a discipline, Brunner explains, refers to the basic concepts and principles of the discipline and their interrelationships. Only students who master this basic structure can achieve meaningful learning so that they can incorporate new material into their existing experience and establish a well-developed and systematic knowledge framework (Gulacar et al., 2022). From the one hundred core concepts in Study 1, the concepts of basic chemical units (e.g., acid and alkali salt), basic principles (e.g., the law of mass conservation), and changes in substance (e.g., various chemical reactions) were selected. These core concepts largely covered the "basic structure" of chemistry.

Currently, most of the existing research on conceptual structure focuses on certain chemical topics and has a single method for concept selection. Mai and colleagues (2021) extracted twenty-four core concepts related to chemical equilibrium using a relevance rating questionnaire. Gulacar and colleagues (2020), using word association test, asked students to list at least ten words they thought of when they read each of nine stimulus words related to core concepts commonly introduced in general chemistry. These studies reflect well the core concepts of certain chemical topics that researchers have focused on, but these core concepts are not yet representative of chemistry as a whole.

Overall, the diverse and objective methods used in Study 1 ensured the scientific nature of the selected core concepts, and it is hoped that researchers will be able to use them as a general reference and fully implement them in future teaching processes.

Conceptual structure

The results of teachers' and students' conceptual structures in Study 2 showed that three-dimensional solutions were appropriate for the conceptual structures. Each dimension was a good reflection of the basic characteristics of chemistry.

Chemistry is the science of substances' composition, structure, properties, and reactions and their laws and principles (K. Taber, 2013). An important purpose of chemistry is the formation of new substances through reactions, including separating a substance under certain conditions or forming new substances formed by multiple substances under certain conditions. According to the result of Study 2, Dimension 1 on the shift from reactive to material conceptual attributes well represents the essence of chemistry science. Dimension 2 reflects the shift from relational to structural conceptual attributes. According to some chemical educators, Chemistry is a subject that focuses on the relationship between the structures of various substances (Erduran & Kaya, 2019; Handtke & Bögeholz, 2022; K. Taber, 2013). Clarifying these relations allows us to prepare the theoretical conditions for creating new substances. Dimension 3 reflects the shift from fundamental to applied conceptual attributes. Chemistry is a science that falls halfway between basic and applied discipline (Doren & Duffy, 2016). The objective substances (e.g., molecules, atoms, etc.) and their structures and properties studied in chemistry often have a wide range of applications in real life, many of the research discoveries made in chemistry are closely related to the many aspects of daily living practice (Cooper et al., 2019).

From a conceptual point of view, because the one hundred concepts selected in Study 1 cover the whole chemical discipline, the results of teachers' and students' classification of these core concepts were more complex and scattered than in existing research that focused on a single topic in chemistry. For example, in the conceptual structure study of the atomic structure (Lin et al., 2022), the concepts related to atomic structure and electronic configuration were classified into one cluster, while the periodic table, periodic law and element properties were classified in another cluster. In the present study, the two clusters of concepts mentioned above appeared to be mixed in both teachers' and students' classifications. This does not mean that the classification in Study 2 was unreasonable but may be related to chemistry textbooks and teachers' teaching methods, which will be explained in the later part.

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From the MDS results it can be seen visually that the classification of high-achieving students is more concentrated than that of low-achieving students. That is, high-achieving students are better able to establish inter-concept relationships based on their understanding of the concepts when classifying them.

The results could be due to the difference in meaningful learning ability between the two groups of students. Specifically, when learning a new concept, high-achieving students tend to make a conscious effort to find connections to the knowledge they learned previously. In the process, they can incorporate new concepts into their existing knowledge, thereby consolidating and extending their chemical knowledge framework, whereas the low-achieving students arbitrarily add new concepts to the existing knowledge framework. This rote learning style may encourage students to fail to apply the same tactic when the chemical problem is slightly different from the ones they have met before. These results were similar to the previous study. For example, Gulacar et al. (2022) divided students into high- and low-achieving students according to their previous performance in chemistry courses and also found that the conceptual structure of the high-achieving students was more organized, whereas the low-achieving students appeared disorganized, reflecting that they did not establish relationships between chemical concepts based on their understanding.

As the differences in conceptual structure as determined by the MDS results are very subjective, it was necessary to further compare the differences in CA results between the two groups of students. For example, the CA results showed that there were differences between the two groups of students in category 6. The high-achieving students classified category 6 as "Concepts of redox reactions", but the low-achieving students classified it as "Reduction".

These differences between the two student groups may be due to the teachers' teaching materials and the students' learning order. In particular, the arrangement of concepts in textbooks is often the most important factor influencing students' conceptual structure (Wolfer, 2000). In textbook compilation, relevant concepts are compiled in the same chapters, although these concepts do not necessarily belong to the same category due to their different nature. For example, students tend to put the "Colloid" and "Tyndall effect" together, perhaps because these two concepts are introduced in the same chapter of the textbook. As can be seen roughly from the clustering results in Study 2, this phenomenon is more common among low-achieving students.

In addition, recently learned or reviewed concepts are more likely to be classified appropriately in the process of building conceptual structure. According to the recency effect, people tend to be familiar with the most recently presented information. This memory performance advantage may mean that low-achieving students are able to appropriately classify recently learned concepts, whereas for those learned early, they are more likely to classify them separately or incorrectly. This indirectly confirms previous findings that those who are able to understand more inter-conceptual relations are less influenced by external factors unrelated to the concepts themselves when understanding and classifying them because they have a more solid conceptual structure (Gulacar et al., 2022; Wilson, 1998).

Conclusion and implications

In Study 1, one hundred chemistry concepts were selected as core concepts. They were identified using personal interviews, material evaluation, and the questionnaire method. Based on these core concepts, Study 2 further explored the conceptual structures of chemistry teachers and students in upper-secondary school using the MDS method, and the results showed that three-dimensional solutions were appropriate. In addition, this study also used CA methods to further explore the structural differences between high- and low-achieving students. The results showed that the conceptual structure of students with high-achieving students was more scientific than that of the low-achieving students.

Based on the overall findings, there are several implications for future research. Firstly, our potential and most important aim of this research was to create a reference that can be used to analyze the conceptual structures of general chemistry of upper-secondary school students. Based on the viewpoint, the structure can be used as an assessment tool for teachers to predict why some students struggle with some concepts. Teachers can improve students' learning by finding the parts of students' cognition that do not have a reasonable conceptual structure and targeting their instruction.

However, with the development of science and technology, many emerging substances are gradually synthesized by chemists, and many innovative techniques are gradually adopted. Students learn from diverse knowledge of chemical concepts through textbooks and the Internet, resulting in a change in the core concepts and conceptual structure in their minds. Therefore, teachers and students can perhaps use these core concepts and teachers' conceptual structure as a universal reference to adapt their teaching and learning objectives, while researchers can continue to incorporate new ideas in the future to create a more widely accepted standard concept and structure.

In addition, the diversity and variability of concepts and teachers' and students' conceptual structures can be seen as a prompt for future research. Specifically, future studies will be conducted to invite diverse populations to enable researchers to better understand expert thinking around chemical concepts, establish a more widely accepted preference for structure, and guide students to actively build a consolidated and refined conceptual structure.

Declaration of Interest

The authors declare no competing interest.

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