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STUDENTS' CONCEPTUAL STRUCTURES REGARDING REDOX REACTION: COMBINING MULTIDIMENSIONAL SCALING AND HIERARCHICAL CLUSTER ANALYSIS APPROACHES

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Abstract. *Redox reaction is a core chemical concept. However, its abstract nature makes it very difficult for students. Students' conceptual structure reflects their mastery of concepts, which helps teachers implement targeted educational strategies. This study aimed to explore the conceptual structures of redox reaction held by students (grades 10 to 12) by employing MDS and HCA. A total of 606 students participated, with 195 students in 10th grade, 202 in 11th grade, and 209 in 12th grade. The results indicated that three-dimensional solutions were appropriate for the conceptual structures of 10th and 12th graders, while 11th graders demonstrated two-dimensional solutions. All students grouped the 15 concepts related to redox reaction into two large clusters: metrology and the redox reaction process. Moreover, both 10th and 12th graders further subdivided the 15 concepts into four subclusters: metrology, oxidation process, reduction process, and chemical reaction. Students' conceptual structures were rational across all three grades. The conceptual structures of 10th and 12th graders were more refined than those of 11th graders, and there was no significant difference between the conceptual structures of 10th and 12th graders. 11th graders learned about electrochemistry and tended to confuse concepts related to redox reaction with those related to electrochemistry.*

Keywords: *conceptual structure, redox reaction, multidimensional scaling (MDS), hierarchical cluster analysis (HCA)*

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Introduction

Redox reaction is a core chemical concept taught throughout the upper-secondary chemistry curriculum. Knowledge of redox reaction is fundamental to much chemical knowledge, such as electrochemistry. However, due to the abstract nature of the concepts related to redox reaction and the limited exposure to them in daily life, it is often difficult for students to properly understand redox reaction (Brandriet & Bretz, 2014; Masykuri et al., 2019; Rosenthal & Sanger, 2012).

Conceptual structure refers to the cognitive representation of a concept within an individual's mind, encompassing each of the concept's components and the relationship among those components (Lin et al., 2022; Qian, 2008). A long-held assumption in cognitive and educational psychology holds that an individual should comprehend the interrelationships between concepts to be knowledgeable and aware of a certain domain (Goldsmith et al., 1991). In the process of understanding the interrelationships between concepts, the individual develops a conceptual structure of a certain domain in his or her mind, also called a knowledge structure (Hayes-Roth, 1977) or cognitive structure (Atabek-Yigit, 2018). Piaget's theory of cognitive development posits that as an individual's knowledge expands, their cognitive structure undergoes ongoing development and enhancement (Supratman, 2013). In other words, students' conceptual structure may change as existing knowledge establishes new connections with new knowledge (Casas-García & Luengo-González, 2013).

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Based on the above analysis, it is essential to reveal the conceptual structures of upper-secondary school students at different grades concerning redox reaction. It can facilitate the accurate assessment of students' conceptual mastery of redox reaction at various grades and provide valuable insights for educators to implement targeted teaching methods for students at different stages of learning.

However, little existing research has focused on the conceptual structures of students regarding redox reaction (Chiang et al., 2014; Tang et al., 2022), and even less on the development of students' conceptual structures regarding redox reaction (Chiang et al., 2014).

Multidimensional Scaling and Hierarchical Cluster Analysis

In the field of science education, various methods have been employed to understand the organization of concepts within the minds of individuals or groups, including concept maps (Burrows & Mooring, 2015; Edmondson, 2005; He et al., 2023), word associations (Gulacar et al., 2015; Gulacar et al., 2022; Nakiboglu, 2008), pathfinder networks (Casas-García & Luengo-González, 2013; Fesel et al., 2015), factor analysis (Mai, Qian, Li et al., 2021; Tang et al., 2022), reaction time technique (Mai, Qian, Lan et al., 2021), multidimensional scaling (MDS) (Lin et al., 2022; Qian et al., 2023), and hierarchical cluster analysis (HCA) (Lin et al., 2022; Qian et al., 2023).

Among these measures, MDS stands out as it's particularly advantageous for visualizing conceptual structure. MDS can create spatial maps that demonstrate the relative distances between objects, making it highly intuitive. It can also identify potential variables that determine multiple objects and depict them graphically in low-dimensional space, such as two-dimensional or three-dimensional space. The number of potential variables corresponds to the dimensions of the graph. In the spatial graph of potential variables, data points represent the objects under investigation, with closer proximity indicating greater similarity in terms of dimensional features (Luo & Zhao, 2005). Consequently, MDS enables researchers to quantitatively assess the similarity among concepts.

However, the interpretation of MDS solutions is subjective (Hout et al., 2013). Different groupings of items will result in different potential variables. To address this issue, further analysis of the spatial coordinate values of the items using cluster analysis can be conducted (Lin et al., 2022). Cluster analysis allows categorization based on the distance among items. In the field of education and psychology, researchers commonly employ the *K*-Means cluster and HCA for data analysis. *K*-Means cluster is suitable when the number of clusters is known, while HCA is preferred in cases where the number of clusters is uncertain. In this study, HCA was utilized for analysis due to the uncertainty of the number of clusters of concepts in the students' conceptual structures regarding redox reaction.

Based on the previous analysis, MDS and HCA were employed in this study to explore and analyze students' conceptual structures of redox reaction, respectively.

Research Questions

Prior research has been deficient in measuring and comparing changes in students' conceptual structures across different grades. This study utilized MDS and HCA to explore and analyze students' conceptual structures of redox reaction, respectively. The following were research questions that this study attempted to address.

1. What are the conceptual structures of redox reaction held by 10th, 11th, and 12th graders, respectively?
2. What are the similarities and differences among the conceptual structures of redox reaction in the minds of 10th, 11th, and 12th graders?

Research Methodology

General Background

This study conducted a questionnaire survey on 195 Grade 10 students, 202 Grade 11 students, and 209 Grade 12 students during the 2022-2023 academic year. This research was divided into three steps.

Firstly, the participants categorized 15 concepts closely related to redox reaction based on similarity. Then, MDS and HCA were applied to explore and analyze students' conceptual structures of redox reaction, respectively. Lastly, the similarities and differences among the conceptual structures of 10th, 11th, and 12th graders regarding redox reaction were analyzed.

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Participants

The subjects of the study were students randomly selected from two upper-secondary schools with different academic levels in Guangzhou, Guangdong Province, China. Participants' demographic information is displayed in Table 1.

Before participating in the survey, all students had learned the knowledge of redox reaction in the compulsory curriculum of chemistry. Furthermore, 11^{th} graders had completed the knowledge of electrochemistry, while 12^{th} graders had finished all upper-secondary school chemistry knowledge and a round of comprehensive review in preparation for the college entrance exam. All subjects were informed in advance of the purpose of the test and participated voluntarily.

Table 1
Demographic Characteristics of Participants

Students	*N*	Recovery rate / %	Age		Gender	
			M	*SD*	Male	Female
10^{th} graders	195	84.4	14.98	.23	101	94
11^{th} graders	202	90.6	16.02	.28	122	80
12^{th} graders	209	91.3	17.99	.32	118	91

Instrument and Procedures

The instrument was a card-sorting questionnaire involving 15 items (as shown in Table 2). In our previous study, we identified 15 concepts that are critical to students' understanding of redox reaction through content analysis, questionnaire survey, and interview (Tang et al., 2022). Given the objectivity, credibility, and representativeness of the results, these 15 concepts were chosen as items that are closely related to redox reaction in this study. The items in the questionnaire were disorganized, with no indication of relevance or classification.

The card-sorting questionnaire was sent to the students (grades 10 to 12), and the 15 items were freely classified according to their thoughts. There was no right or wrong classification, and the basis and number of categories for classification were determined by individuals. Each item was individually classified into one category without being omitted or repeatedly selected. Participants should complete the questionnaire within 20 minutes, and discussion during the process was forbidden.

Table 2
15 Items Closely Related to Redox Reaction

Number	Item	Number	Item	Number	Item
1	Conservation of gain and loss electrons	6	Oxidation numbers	11	Reduced
2	Electron transfer	7	Oxidation state changes	12	Reduction
3	Oxidizing ability	8	Reducing agent	13	Oxidized
4	Oxidizing agent	9	Oxidation	14	Oxidation product
5	Number of gain and loss electrons	10	Reducing ability	15	Reduction product

Note: The item "conservation of gain and loss electrons" refers to the principle that the number of electrons gained is equal to the number of electrons lost in a redox reaction (Tang et al., 2022).

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Data Analysis

The data analysis consisted of three steps. Firstly, the data from students at each grade were used to generate a dissimilarity matrix for the corresponding grade level. A 15x15 dissimilarity matrix was created by assigning a score of 1 to item pairs in different groups and a score of 0 to item pairs in the same category (Qian et al., 2023). Thus, three dissimilarity matrices were obtained.

Then, three dissimilarity matrices were analyzed via the MDS program of SPSS 23.0 to derive the conceptual structures of redox reaction for 10th, 11th, and 12th graders, respectively. The Euclidean squared distance was used to calculate the distance between items.

Finally, HCA was conducted to analyze students' conceptual structures of redox reaction by Ward's method. The data used by HCA were the squared Euclidean distance between items.

Research Results

The Conceptual Structures of Redox Reaction Held by Students

Researchers used Stress and RSQ to evaluate the quality of the data fit while employing MDS to analyze data. Stress indicates the fitness of the statistical results to the original data; the smaller, the better. Lower stress values (below .10) indicate a better fit (Roy, 2020), as shown in Table 3. RSQ indicates the square of the regression coefficient, reflecting the proportion of the variance of the original data explained by the low-dimensional space; the closer the RSQ is to 1, the better.

Table 4 shows the values of Stress and RSQ in two- and three-dimensional solutions for students (grades 10 to 12). Three-, two- and three-dimensional solutions were appropriate for students in Grades 10, 11, and 12, respectively, owing to the stress and RSQ. In other words, the conceptual structures of redox reaction in the minds of 10th, 11th, and 12th graders were three-, two-, and three-dimensional, respectively (shown in Figure 1).

It is worth noting that both the two- and three-dimensional solutions demonstrated a good fit with the data for 11th graders. However, upon a thorough analysis of the images from the two-dimensional and three-dimensional solutions, it was discovered that the 15 items were clustered in two locations, with each cluster being closely grouped. Furthermore, the two-dimensional solution allowed for a more intuitive representation of the aggregation among items. Therefore, the two-dimensional solution was accepted to serve as the conceptual structure of redox reaction for 11th graders.

To represent more clearly and intuitively the clustering among items in the three-dimensional solution image, Figures 2 and 3 present 10th and 12th graders' two-dimensional mapping images of the three-dimensional solutions (Lin et al., 2022).

Table 3
Stress Values and Corresponding Goodness of Fit

Stress	Goodness of Fit
.200	Poor
.100	Fair
.050	Good
.025	Excellent
.000	Perfect

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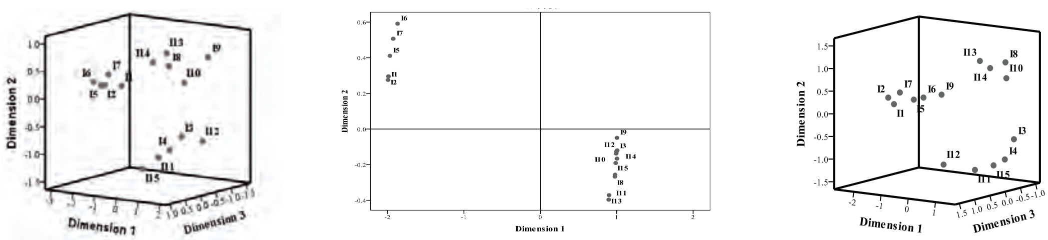
Table 4
Stress and RSQ Values Determined by MDS

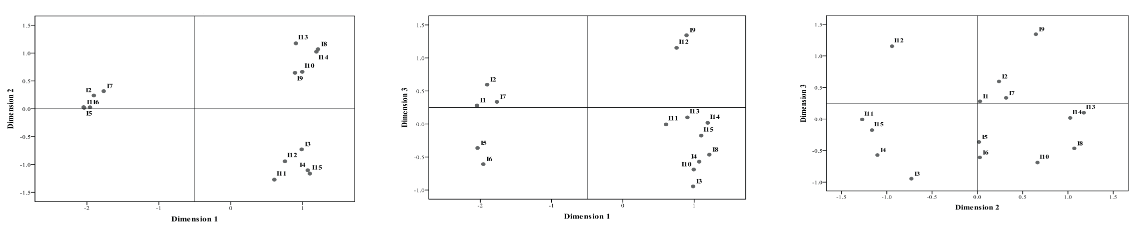
Students	Model Fit			
	Two Dimensions		Three Dimensions	
	Stress	RSQ	Stress	RSQ
10th graders	.124	.947	.087	.956
11th graders	.026	.999	.030	.998
12th graders	.130	.943	.092	.958

Figure 1
Conceptual Structures of Students in Grades 10, 11, and 12



(a) 10th graders (b) 11th graders (c) 12th graders

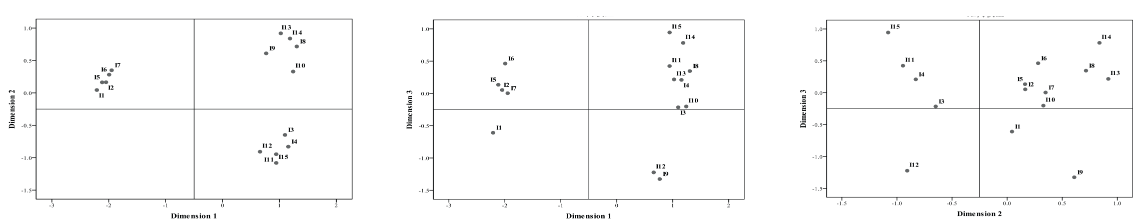
Figure 2
Two Dimensional Projections of the Three-dimensional Solution of 10th Graders



(a) D1 and D2 (b) D1 and D3 (c) D2 and D3

Note: "D" refers to dimension.

Figure 3
Two Dimensional Projections of the Three-dimensional Solution of 12th Graders



(a) D1 and D2 (b) D1 and D3 (c) D2 and D3

Note: "D" refers to dimension.

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A three-dimensional solution was appropriate for the conceptual structure of 10th graders. The names of the three dimensions were as follows, based on the shared meaning of items in each dimension.

First, D1 was named "metrology/redox reaction process". The left side of D1 included five items related mostly to metrology, while ten items on the right were related to the redox reaction process, as demonstrated in Figure 2(a). Second, D2 was named "reduction process/oxidation mechanism". Five items related to the reduction process were observed on the opposing side of D2, while ten items associated with the oxidation mechanism were observed on the positive side of D2. Finally, D3 was named "redox reaction mechanism/chemical reaction". The lower side of D3 gathered items related to the redox reaction mechanism, while the upper side gathered items "oxidation" and "reduction", both referred to chemical reactions, as shown in Figure 2(b).

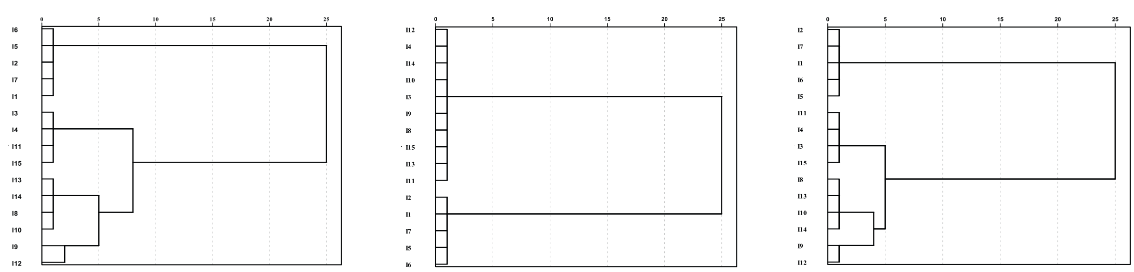
A two-dimensional solution was appropriate for the conceptual structure of 11th graders. In the two-dimensional solution image, quadrants were numbered from one to four (Q1, Q2, Q3, and Q4) in a counterclockwise order setting up with the top-right quadrant (Yilmaz & Kapkin, 2021). As illustrated in Figure 1(b), 15 items were mainly clustered in Q2 and Q4. Five items in Q2 related to metrology, which was consistent with the items to the left of D1 in the three-dimensional image of 10th graders. Ten items in Q4 were related to the redox reaction process, which was consistent with the items to the right of D1 in the three-dimensional image of 10th graders.

A three-dimensional solution was appropriate for the conceptual structure of 12th graders. A careful comparison of Figures 2 and 3 reveals that in terms of the distribution of concepts in each dimension, 12th and 10th graders had extremely similar conceptual structures. As a result, each dimension in the three-dimensional solution of 12th graders was labeled as follows. The D1, D2, and D3 were named "metrology/redox reaction process", "reduction process/oxidation mechanism", and "redox reaction mechanism/chemical reaction", respectively.

Conceptual Clustering in the Conceptual Structures of Redox Reaction Held by Students

The dendrograms obtained by HCA are shown in Figure 4. 15 items were divided into two large clusters including four sub-clusters by 10th and 12th graders, while they were split into two clusters only by 11th graders. Table 5 displays the classifications examined by HCA of students in different grades.

Figure 4
The Dendrograms Obtained by HCA of 10th, 11th, and 12th graders



(a) 10th graders (b) 11th graders (c) 12th graders

Table 5
The Classifications Obtained by HCA of 10th, 11th, and 12th graders

Students	Large clusters	Sub-clusters
10th graders	Metrology	(1) Metrology
	Redox reaction process	(2) Oxidation process; (3) Reduction process; (4) Chemical reaction
11th graders	Metrology	-
	Redox reaction process	-
12th graders	Metrology	(1) Metrology
	Redox reaction process	(2) Oxidation process; (3) Reduction process; (4) Chemical reaction

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As demonstrated in Table 5, all three grade students divided the 15 items into two large clusters. One cluster included five items regarding metrology, and the other comprised ten items concerning the redox reaction process.

10th and 12th graders continued to subdivide the cluster "redox reaction process" into three subclusters, in contrast to 11th grades. The three subclusters were "oxidation process", "reduction process", and "chemical reaction". Thus, 10th and 12th graders split the 15 items into four sub-clusters: "metrology", "oxidation process", "reduction process", and "chemical reaction".

Discussion

In this study, MDS and HCA were utilized to explore and analyze the conceptual structures of students (grades 10 to 12) regarding redox reaction, respectively. The similarities and differences among the conceptual structures of redox reaction in the minds of 10th, 11th, and 12th graders were analyzed.

Similarity of Conceptual Structures Held by Students in Three Grades

Although the organizations of the conceptual structures regarding redox reaction were not the same for the students in all three grades, their conceptual structures were all rational. To begin with, students categorized 15 concepts relevant to redox reaction correctly and with clear boundaries. The MDS results showed that the 15 concepts were distinctly and unambiguously categorized by students, with a high degree of concentration within each category. It indicated that students were able to clarify the interrelationships of 15 concepts relevant to redox reaction.

Second, there was a good scientific connection among the concepts clustered into a category. The HCA results revealed that the students in all three grades grouped the 15 concepts into the same two large clusters. The names and specific distribution of the concepts are presented in Table 6.

Table 6
The Concepts Included in Two Large Clusters

Large cluster	Name	Concepts
1	Metrology	Electron transfer, Oxidation numbers, Oxidation state changes, Number of gain and loss electrons, Conservation of gain and loss electrons
2	Redox reaction process	Oxidizing agent, Oxidizing ability, Reduced, Reduction product, Reducing agent, Reducing ability, Oxidized, Oxidation product, Oxidation, Reduction

In large cluster 1, the essence of the redox reaction is electron transfer, involving electron gain and loss. The number of electrons lost equals the number of electrons gained, which is what the concept "conservation of gain and loss electrons" means (Tang et al., 2022). Due to electron transfer, the oxidation numbers of the element will change.

In large cluster 2, the oxidizing agent has the oxidizing ability and is reduced during a reduction to produce reduction products. Meanwhile, a reducing agent has a reducing ability and is oxidized in the process of oxidation to produce oxidation products.

In conclusion, the 15 concepts connected to redox reaction were categorized and then stored in students' minds with clear boundaries between categories. Meanwhile, concepts in each category had a scientific connection to each other. That is, students in all three grades were able to comprehend the meaning of the 15 concepts and their interrelationships.

Differences of Conceptual Structures Held by Students in Three Grades

The conceptual structures of 10th and 12th graders were more refined than those of 11th graders, while there was no significant difference between the conceptual structures of 10th and 12th graders.

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As shown in Figure 4, 11th graders clustered the 15 concepts related to redox reaction into two categories, while both 10th and 12th graders further subdivided the 15 concepts into four categories, each with chemical significance and more refinement. The specific concept distribution and names of the four subclusters are shown in Table 7.

Comparison of Tables 6 and 7 shows that 10th and 12th graders continued to subdivide the cluster "redox reaction process" into three subclusters. The three subclusters were "oxidation process", "reduction process", and "chemical reaction". A redox reaction consists of two half-reactions, namely an oxidation and a reduction. The redox reaction process encompasses both the oxidation process and the reduction process. Consequently, additional categorization by 10th and 12th graders was justified, suggesting that 10th and 12th graders exhibit a more optimal cognitive processing of the 15 concepts.

11th graders had just completed the knowledge of electrochemistry at the time of the survey. In an electrochemical device, oxidation and reduction occur at different sites and are usually analyzed separately. For example, oxidation occurs at the anode and reduction at the cathode. Therefore, 11th graders were expected to be able to further refine their categorization of the cluster "redox reaction process". However, it is surprising that 11th graders did not subdivide the cluster "redox reaction process" into "oxidation process" and "reduction process".

Interviews with upper-secondary chemistry teachers and 11th graders revealed the following two causes. Firstly, 11th graders had forgotten their understanding of redox reaction to a larger extent. In China, upper-secondary school students are studying the knowledge of redox reaction in their first year of chemistry curriculum. At the time of the survey, it had been a long time since 11th graders had studied redox reaction in depth. As a result, students forgot the meaning and relationship of concepts related to redox reaction to a larger extent.

Secondly, the knowledge of electrochemistry interfered with the conceptual structure of 11th graders regarding redox reaction. Many of the concepts related to electrochemistry are very abstract, such as anode, cathode, reduction potential, and so on. Students need to use the knowledge of redox reaction to understand these concepts. For example, the site of the oxidation reaction is the anode. Thus, students tended to confuse concepts related to redox reaction with those related to electrochemistry and then affected the conceptual structure of redox reaction for 11th graders.

In an earlier study, Chiang et al. (2014) explored the conceptions of Taiwanese, China upper-secondary school students (grades 10 to 12) regarding redox reactions via a two-tier test. It was found that some 11th graders understood redox reactions better than the 12th graders. The researchers attributed this finding to the fact that the 12th graders studied electrochemistry, which led to conceptual confusion between redox and electrochemical theories. This result is consistent with our results for the following reason.

In the Chinese mainland, students finish learning electrochemistry in their sophomore year of upper-secondary school. Thus, 11th graders are disturbed by their electrochemical knowledge in understanding redox reactions compared to 10th graders. Although 12th graders also learned about the knowledge of electrochemistry, they were less likely to be disturbed by the knowledge of electrochemistry in their understanding of redox reactions. At the time of the survey, 12th graders had completed all upper-secondary school chemistry knowledge and a round of review in preparation for the college entrance exam. Consequently, they developed a stronger, more refined, and systematic understanding of the core concepts of redox reaction as they solved problems in complex systems.

Notably, our work is still significant even if Chiang et al. (2014) studied the knowledge structures of redox reactions that students (grades 10 to 12) held. First, the students in the two studies had different knowledge foundations. While students in the Chinese mainland learn about electrochemistry in their sophomore year of upper-secondary school and spend their senior year of upper-secondary school doing multiple rounds of review for the college entrance examination, students in Taiwan, China, study electrochemistry in their senior year of high school. Students' comprehension of redox reactions is affected by both their knowledge of electrochemistry and the several rounds of knowledge reviews.

Second, this study is the initial attempt to utilize MDS and HCA to explore and analyze the conceptual structure of redox reactions in students' minds. The conceptual structure obtained in this study gives access to the spatial representation of the conceptual structure as well as the conceptual clustering within it (Lin et al., 2022; Qian et al., 2023), providing insight into the degree of refinement of students' understanding of redox reactions.

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Table 7
The Concepts Included in Each Subcluster

Subcluster	Name	Concepts
1	Metrology	Electron transfer, Oxidation numbers, Oxidation state changes, Number of gain and loss electrons, Conservation of gain and loss electrons
2	Oxidation process	Oxidizing agent, Oxidizing ability, Reduced, Reduction product
3	Reduction process	Reducing agent, Reducing ability, Oxidized, Oxidation product
4	Chemical reaction	Oxidation, Reduction

Conclusions and Implications

This study utilized MDS and HCA to explore and analyze students' conceptual structures of redox reaction, respectively. In the minds of 10th, 11th, and 12th graders, the conceptual structures of redox reaction were three-, two-, and three-dimensional, respectively. The 15 concepts related to redox reaction were grouped into two large clusters by students in all three grades. Furthermore, both 10th and 12th graders subdivided the 15 concepts into four subclusters.

Students' conceptual structures were rational across all three grades. The conceptual structures of 10th and 12th graders were more scientific and rational than those of 11th graders, and there was no significant difference between the conceptual structures of 10th and 12th graders.

The preceding conclusions offer two insights. First, teachers can tailor instruction to students based on the conceptual structures of students at different grades. For instance, teachers should assist students in reviewing the definitions of concepts relevant to redox reaction and their interrelationships before instructing 11th graders on electrochemistry. It will help 11th graders develop a scientifically sound conceptual structure for redox reactions and will also contribute to their understanding of electrochemistry.

Second, subsequent researchers can examine students' conceptual structures across disciplines. Different disciplines may cover the same knowledge. For example, the knowledge of molecular structure is found in both upper-secondary school chemistry and biology curriculums. The concepts closely linked to this knowledge are distributed in different disciplines, so the corresponding conceptual structures in students' minds may integrate knowledge from multiple disciplines. Researchers can select closely related concepts of a particular piece of knowledge from multiple related disciplines so that the resulting conceptual structure can be useful in adequately reflecting students' understanding and organization of knowledge. It will support teachers in implementing effective teaching strategies that foster students' integrative thinking and interdisciplinary problem-solving skills.

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Declaration of Interest

The authors declare no competing interest.

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