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Fostering students' geographical synthetic thinking using geographic subject mind maps

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The term "geographical synthetic thinking" is taken from the latest Chinese version of the "Geography Curriculum Standards" (General High School 2017 edition, Compulsory Education 2022 edition) and is one of the four core competencies prioritized in the teaching of geography at the secondary-school level. This study proposes that using geographic subject mind maps improves students' geographical synthetic thinking and develops a set of geographic subject mind map (GSMM) drawing standards for teachers and matching standards and suggestions for teaching applications. Seven geography teachers and their students from eight class sections in seven provinces and cities in China were recruited to participate in the study. The teachers taught students how to use geographic subject mind maps designed to develop students' geographical synthetic thinking in the geography classroom. After 4–5 experimental lessons, the geographical synthetic thinking level of the 267 valid student participants showed a significant improvement, with a statistically significant difference between pretest and posttest scores. The teachers' level of application of geographic subject mind maps in teaching was significantly and positively correlated with the students' improvements in geographical synthetic thinking, demonstrating that the standardized use of geographic subject mind maps in accordance with teaching application standards can effectively improve students' geographical synthetic thinking levels.

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Introduction

Systems thinking is the process of understanding complex systems rather than in parts (Arnold and Wade, 2015). It offers a means of comprehending and interpreting our complex world (Orgill et al. 2019), emphasizing the relationship between systems (the basic units of motion in the natural world) and thinking (the mental models of real-world phenomena), which are developed based on feedback to better mirror reality. Recently, systems thinking has been perceived as a conceptual framework to think and learn about various systems and has found applicability across the fields of education, science, business, social life, and personal growth (Cabrera and Cabrera, 2023). Geography, which studies the Earth's surface—a complex system—adheres to a tradition of systems thinking. Therefore, the content of geography naturally lends itself to the cultivation of systems thinking in students. Emphasis has been placed on nurturing systems thinking skills in the field of geographical education, with many studies adopting geographical instructional content to foster systems thinking, such as through the teaching of the lithosphere's material cycle, earth systems, water cycle, and climate change (Kali et al. 2003; Assaraf and Orion, 2005; Lee et al. 2019; González, 2022).

Importantly, as a cognitive ability, systems thinking does not possess disciplinary attributes. However, restricting training to universally applicable models of systems thinking is insufficient for geographical education. On one hand, if geography is used merely as a tool for achieving the objectives of other subjects, rather than being respected as an independent field, geographical education could face serious threats (Brooks et al. 2017). On the other hand, as Viehrig et al. (2017) stated, in dealing with geographical systems, systems thinking (the "why") is insufficient, and spatial thinking (the "where") must be incorporated. Pure systems thinking often falls short regarding geospatial attention, thus limiting the understanding of geographical phenomena (Cox et al. 2020). Due to the regional characteristics in the discipline of geography, to understand complex geographical systems, it is necessary not only to have the comprehensiveness, integrity, and dynamism of systems thinking (Cabrera and Cabrera, 2023) but also to give special attention to spatial (regional) differentiation and spatial (regional) relevance as unique elements in the subject of geography. After enriching the connotations of geographical space cognition, systems thinking is known as geographical synthetic thinking.

Geographical synthetic thinking is a method of thinking that recognizes geographic phenomena from a comprehensive, systematic, spatial, and dynamic perspective. This definition is derived from the Chinese National Geography Curriculum Standard (Chinese Ministry of Education, 2017). Chinese scholars like Lin (2017), Wang et al. (2017), Wei and Zhu (2018), Yuan (2020), and Lu et al. (2022) have elaborated on it, dividing it into three dimensions such as factor synthesis, spatiotemporal synthesis, and regional synthesis, which can be further divided into six dimensions. These include geographical factors system thinking, geographical factors interaction thinking, temporal changes thinking, regional differentiation thinking, intraregional synthetic thinking and interregional synthetic thinking (Lu et al. 2022).

Theoretical research on the development of geographical synthetic thinking has identified two influential factors: the knowledge foundation of geographic synthetic thinking and the metacognition of geographic synthetic thinking (Zhu, 2018; Fan et al. 2020). Studies on strategies to cultivate students' geographical synthetic thinking have yielded a wealth of practical results, adopting methods such as problem-based teaching (Ma, 2022; Huang, 2023), GIS-assisted teaching (Guo, 2023; Huang, 2023), and thinking visualization tools such as mind maps (Li, 2019; Du, 2020; Wang, 2022; Li, 2022; Lang, 2023; Gu, 2023).

Mind mapping holds certain advantages in developing students' geographical synthetic thinking, but it also has its limitations. On one hand, mind mapping can help students organize and process knowledge, transform scattered knowledge into a cognitive structure connected by logical relationships, and envision a comprehensive meaning (Jiao, 2014). Its role is similar to tools for visualizing the structure of the mapped knowledge, such as concept maps (diagrams that articulate relationships between concepts). Wehry et al.(2012) utilized concept maps developed by teachers or researchers in 7th-grade geography teaching, and by assessing students' learning through the concept maps they drew, demonstrated the role of concept maps in promoting meaningful learning. Currently, empirical studies on cultivating geographical synthetic thinking using mind maps have proven its effectiveness (Li, 2022; Lang, 2023; Gu, 2023). On the other hand, studies also show that traditional mind maps cannot fully represent the connotations of geographical synthetic thinking (Li, 2019; Du, 2020; Wang, 2022). For instance, Du's (2020) research suggested that mind maps can significantly improve students' elemental and spatiotemporal synthetic skills but not their regional synthetic skills. This is because geographical synthetic thinking is a core literacy skill in geography, and traditional mind maps do not inherently possess the properties unique to geographical thinking, such as spatial (regional) differentiation, geographical element systems, connections between geographical elements, and the evolution of geographical processes. Therefore, this study proposes the concept and framework of the geographic subject mind map. Informed by geographic thought and methodologies and directed towards problem solving, the geographic subject mind map is a visualization tool for synthetic thinking that analyses and synthesizes geographical phenomena from the perspectives of geographical elements (referring to the system of geographical elements, dominant factors, and connections between geographical elements), space (region) (referring to spatial (regional) differentiation), and time (referring to the evolution of geographical processes).

This study uses geographic subject mind maps as a tool to develop students' geographic synthetic thinking and mainly explores the following three questions:

How are geographic subject mind maps drawn?

How are the standards for the teaching applications of accompanying geographic subject mind maps established?

Can the use of geographic subject mind maps effectively cultivate students' geographic synthetic thinking?

Literature review

Theoretical background. The sustainability challenges that the world faces today, such as climate change, urbanization, and ecological degradation, are described as complex and "wicked" (Ho, 2021). Addressing these issues requires the ability to realize the complex interconnections among dimensions of a system (Demssie et al. 2023). Systems thinking is a way of comprehending a system, focusing on the interaction and connection among its components (Zhang and Ahmed, 2020). It can help people identify the interdependence of natural and social phenomena, discover patterns, and construct system concepts, thereby enabling a better understanding of complex global issues (National Research Council, 2012; Demssie et al. 2023). Students are future decision-makers in this rapidly changing world. Consequently, numerous studies have underscored the importance of cultivating systems thinking in education (Arnold and

Wade, 2015; Hmelo-Silver et al. 2017; Roczen et al. 2021). Systems thinking is even considered a core competence in education for sustainable development (Green et al. 2021). Many countries have explicitly included systems thinking in the goals of science education (Cox et al. 2019). One such example is the Next Generation Science Standards of K-12 education in the United States (Yoon and Hmelo-Silver, 2017). In Germany, insights into complex systems represent a fundamental ability in geographic education (Rempfler and Uphues, 2022).

However, recent studies have shown that the systems thinking approach is deficient due to the lack of geospatial embeddedness (Cox et al.2020, 2019; Dessen Jankell et al. 2021); thus, some studies have attempted to enrich systems thinking. For example, Wiek et al. (2011) defined systems-thinking competence as the ability to collectively analyse complex systems across domains (society, environment, economy, etc.) and across scales (local to global). Building on this, Demssie et al. (2023) defined systems thinking competencies as "the ability to recognize the elements and complexity of a system, to understand the interrelationships of the elements, and to appreciate the impacts of the interrelationships at the local, national, and global levels." These studies have infused systems thinking with spatial (regional) cognition, that is, defining systems thinking skills as the ability to recognize the interactions between people and their environment in a particular location, which is the focus of geography (Haubrich, 1992). Geography is the discipline par excellence in dealing with spatial change (International Geographical Union, 2016). Systems thinking enriched with geospatial cognition has a special focus on the spatial (regional) dissimilarities and spatial (regional) correlations of geographic phenomena that are unique to the discipline of geography. As a result, many scholars have renamed enriched systems thinking to various terms, such as "systems thinking in geography" (Cox et al. 2019), "geospatial relational thinking" (Favier and van der Schee, 2014), and "geographical relational thinking" (Karkdijk et al. 2019). This study argues that systems thinking enriched with spatial thinking has a strong geographic disciplinary identity—regional and integrative—and can therefore be called geographical synthetic thinking. This concept is endorsed by the latest version of China's geography curriculum standards (Ministry of Education of the People's Republic of China, 2017; Ministry of Education of the People's Republic of China, 2022) and has become one of the four core literacies that the Chinese Ministry of Education stipulates that secondary school geography courses should focus on cultivating in students.

Geographical synthetic thinking is closely related to systems thinking. This paper posits that the difference between them is merely conceptual, and geographical synthetic thinking can also be understood as geographical systems thinking. Systems thinking focuses on the interactions, feedback, and impacts among system elements, as well as the relationship between the system and its external environment. It emphasizes analyzing problems from a holistic perspective rather than from the viewpoint of individual parts, helping people recognize the complexity and diversity of problems.

Geographical synthetic thinking is a part of systems thinking. Due to the specific object of geographical thinking, i.e., geographical entities in regions and space, its definition highlights a comprehensive, systematic, spatial, and dynamic approach. This is manifested in the complete contemplation of the system of geographical elements and the identification of dominant factors, understanding of the complex relationships among geographical elements, emphasis on the changes of geographical elements over time, differentiation of geographical elements due to space, the comprehensiveness and wholeness of the geographical environment, and the existence of connections between regions. This

kind of geographical synthetic thinking can also be considered as a special term for systems thinking in the field of geography. Its uniqueness lies in its geographical spatial attributes, exhibiting particular focuses, but fundamentally, it belongs to systems thinking.

As geography education focuses on human-environment interactions and how they vary across locations (van der Schee et al. 2014), this matches the holistic (elemental connections), temporal (developmental changes), and spatial (regional characteristics) characteristics emphasized by geographical synthetic thinking (Wei and Zhu, 2018). In the context of geography education, developing geographical synthetic thinking enables students to understand complex geographic systems as well as issues of environmental sustainability and human sustainability and helps students cope with a rapidly changing, interdependent, and complex world (Bednarz et al. 2013). Therefore, it is crucial to develop geographical synthetic thinking.

This study measures students' geographical synthetic thinking skills using the "Geographical Synthetic Thinking Measurement Scale" developed by Lu et al. (2022) (http://luxiaoxu.net/online/qk/dlkxjz/zhsw.htm). The scale includes 24 items, 5 direct measurement effectiveness check items, and 3 objective recognition items (for excluding participants who did not seriously participate in the measurement process, students who failed the objective recognition items are considered invalid observations), totalling 32 items. The scale has undergone multiple quality checks and modifications. The Cronbach's alpha reliability coefficient of the scale is 0.928, which is extremely high; the reliability of the 6 subscales for measuring six thinking dimensions of geographical synthetic thinking are 0.631, 0.735, 0.716, 0.684, 0.786, and 0.752, respectively, all of which exceed the basic requirement of reaching 0.6 for the subscale. The scale reliability is thus validated. The reliability of the subscale composed of 5 effectiveness items is 0.876. The measurement results of this subscale and the correlation coefficient of the measurement results of the 24 items reach 0.837, $P < 0.001$, and the validity is good. Therefore, it can be used for the official test of students' geographical synthetic thinking skills. The scale is a self-reported measurement. The items are designed to be answered with a 5-point scale, by which participants indicate the degree of compliance with the actual situation or description, from 1 to 5 points, where 5 points are awarded if they very much agree, and 1 point is awarded if they do not agree at all. The first 24 measurement items of the scale are used to measure the level of geographical synthetic thinking and are divided into six subclasses to measure its six thinking dimensions: geographical factors system thinking, geographical factors interaction thinking, temporal changes thinking, regional differentiation thinking, intraregional synthetic thinking and interregional synthetic thinking. As each item has a maximum score of 5 points, and each dimension is measured by 4 items, a perfect score is 20 points. The total score for all 24 items measuring geographical synthetic thinking skills is 120 points. However, in this study, all dimension scores and the total score of geographical synthetic thinking were converted to a 100-point grading system, and the converted total score represents the students' level of geographical synthetic thinking.

Empirical evidence. Due to the early application of systems thinking in education and its numerous achievements, the cultivation of geographical synthetic thinking can be further developed on the foundation of systems thinking training. Many studies have shown that students need the assistance of learning tools when developing systems thinking. First, students need clear and scaffolded guidance to develop systems thinking skills, which
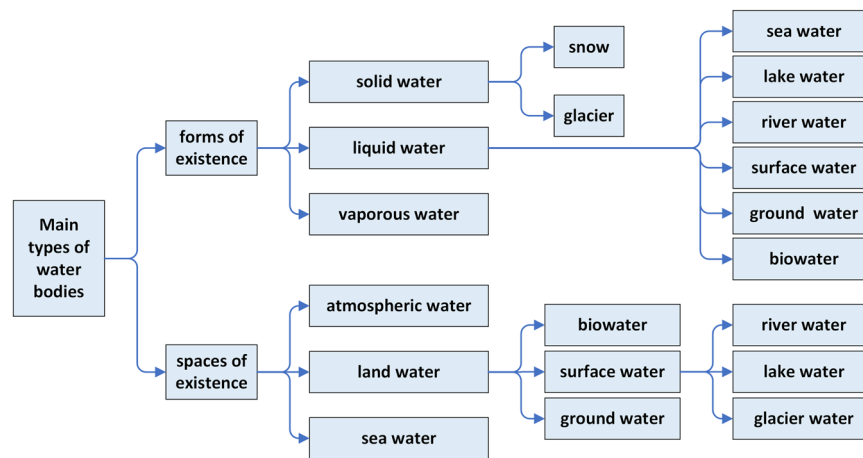
Fig. 1 Example of mind map.

consider the relationships between levels within the system (Hokayem et al. 2015; Tripto et al. 2017; York et al. 2019; Zhang and Ahmed, 2020). Second, some visualization tools or models can meet student needs for learning system reasoning through visually appealing representations (Hmelo-Silver et al. 2017) and have been proven to support the formation of systems thinking (Schwarz and White, 2005; Svoboda and Passmore, 2013). Therefore, many systems thinking advocates have proposed tools for developing student skills in systems thinking, such as system prototypes, graphs of behaviour over time, causal loop diagrams with feedback and delays, system diagrams, flowcharts, and computer modelling. (Monat and Gannon, 2015; Zhang and Ahmed, 2020; Green et al. 2021). Currently, many studies use concept maps (Assaraf and Orion, 2005; Tripto et al. 2013), computer-based cognitive structure diagrams (Kali et al. 2003), causal maps (Cox et al. 2020), and other visualization tools to train systems thinking and have confirmed their effectiveness. However, some scholars have pointed out that when applying these tools or models, special attention should be given to the differences between disciplines and to clarifying the thinking types and objectives they support (Svoboda and Passmore, 2013).

Research question. Based on this understanding of a learning agenda for geographical synthetic thinking, this study proposes a framework for the geographic subject mind map with specific drawing standards covering all six dimensions of geographical synthetic thinking. When teachers use the geographic subject mind map in the classroom, students can improve their basic knowledge of geographical synthetic thinking while learning how to draw the geographic subject mind map; during the process of learning how to use the geographic subject mind map to solve geographical problems, they can internalize analysing and viewing geographical problems from an integrated perspective and improve their metacognition of geographical synthetic thinking.

Therefore, this study puts forward the following hypothesis: if teachers use geographic subject mind maps in a standardized way, they can significantly improve students' geographical synthetic thinking skills; at the same time, it is assumed that the level to which teachers apply geographic subject mind maps while teaching in the experiment impacts the improvement of students' geographical synthetic thinking skills.

Development of a model to improve students geographical synthetic thinking
A mind map begins with a focal point, using connecting words to represent the hierarchical relationships between levels of concepts

(Davies, 2010), as illustrated in Fig. 1. Systems thinking focuses on the interactions, feedback, and impacts among system elements and the relationship between the system and its external environment. It emphasizes analyzing problems from a holistic rather than a piecemeal perspective, helping people to recognize the complexity and diversity of problems. A "mind map" in systems thinking is shown in Fig. 2. Geographical synthetic thinking (for example, comprehensively contemplating the causes of geographical phenomena from both physical and human factors) is part of traditional geographical thinking (which includes geographical synthetic thinking, geographical scale thinking, geographical process thinking, and human-land relationship thinking). Since geographical synthetic thinking is essentially systems thinking, systems thinking with the addition of geographical components becomes geographical synthetic thinking.

This research designed a new type of geographic subject mind map based on general mind maps. The structure of the new geographic subject mind map is displayed in Fig. 3, incorporating three critical dimensions: factor, space, and time. Additionally, Table 1 outlines 13 requirements for designing such a new mind map (these requirements demonstrate how to analyze problems from the perspective of factors, how to consider factors in specific regions, how to reflect the interconnections of factors, how to show the changes of factors over time, and how to display the differences and connections of factors between regions). The map designed according to these 13 requirements is the geographic subject mind map, which will become an independent variable for improving students' geographical synthetic thinking.

Figure 4 shows how a standard geographic subject mind map can demonstrate the thought process in addressing a geographical issue.

Firstly, similar to any mind map, a geographic subject mind map needs to clearly identify the issue to be analyzed. However, it must be a geographical problem, which differentiates a geographical thinking mind map from general mind maps or systems thinking mind maps. For example, in Fig. 4, it analyses the issue of transferring the silkworm production base and meets Q1.

Secondly, think about geographical issues from the perspective of factors. On one hand, the analysis of geographical issues can consider both physical and human factors, identify the factors closely related to the issue, and list them for analysis. Notably, there is a distinction between geographical subject mind maps and systems thinking mind maps in contemplating geographical issues from the factor's perspective. While systems thinking maps require listing the system's components, geographic subject mind maps require listing both physical and human factors of the geographical system, indicating a difference in categorization.
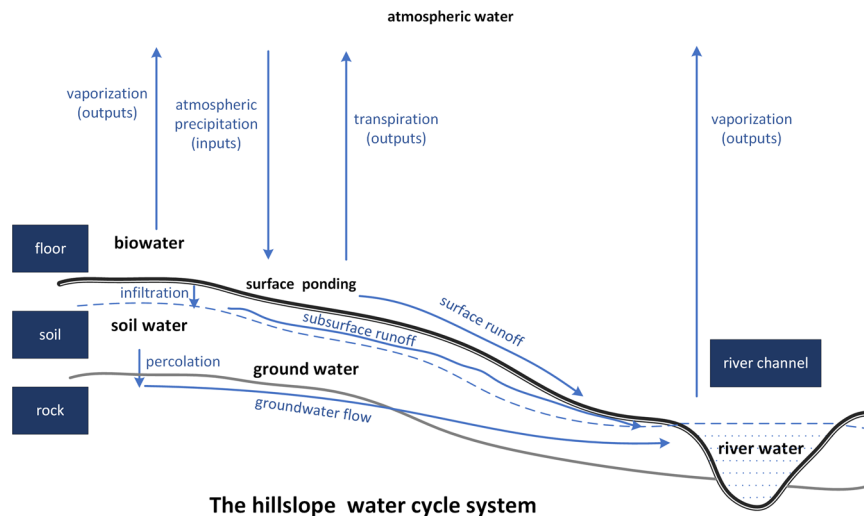
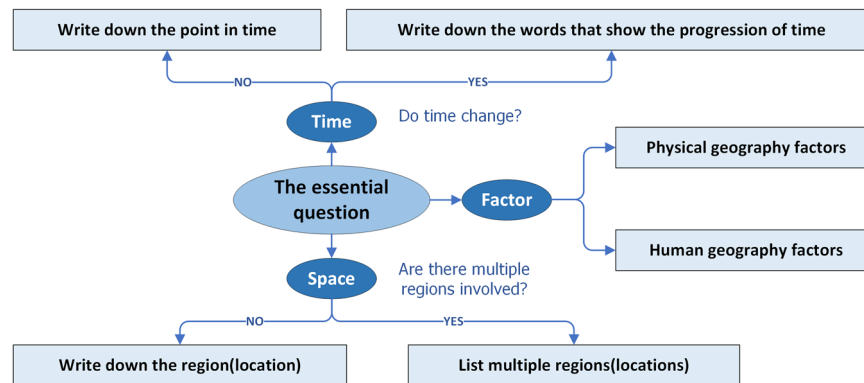**Fig. 2 Example of mind map in systems thinking.**

Fig. 3 Geographic subject mind map model.

Figure 4 considers both physical and human factors to determine that the city, land, and labour (human factors) and climate (physical factors) are closely related to this problem and lists and analyses these factors to meet F1, F2, and F3. On the other hand, geographic subject mind maps require placing factors within specific spaces (regions) for consideration, which is not a particular focus of systems thinking mind maps. For instance, Fig. 4 shows the analysis of factors corresponds to the "Guangxi" and "Jiangsu-Zhejiang" regions, meeting F4. Moreover, issues should be considered from the perspective of factor connections. For example, in the analysis of human factors, there is an arrow pointing from "city" to "land" and one pointing from "city" to "labour force"; these two red arrows indicate the interactions between factors, meeting F5.

Thirdly, think about geographical issues from a temporal perspective. Consider the timing of the factors and whether they change over time. For Fig. 4, in the time-related term "since the 21st century", the word "change" is marked, and red words such as "increase", "has decreased", "rise", and "reduction" describe the changes in factors over time, not meeting T1 but meeting T2.

Fourthly, consider geographical issues from a regional perspective. If a geographical problem involves multiple areas, it necessitates considering the regional differences in geographical factos. Figure 4 analysing the differences in the factors in the "Guangxi" and "Jiangsu-Zhejiang" regions, such as land and labour factors, meets S1 and S2; the factor differences between these two regions lead to regional differentiation, meeting S3.

On one hand, analyze geographical issues from the perspective of vertical integration. The interconnection and impact of factors within a region form the overall characteristics of the area. For example, after comprehensively analysing the factors of city, land, and labour in the Jiangsu-Zhejiang region, Fig. 4 concludes that, "The cost of silkworm production in Jiangsu and Zhejiang has increased, leading to a reduction in the scale of production". The map uses a dotted line to circle the analysis of the factors, meeting S4. On the other hand, analyze geographical issues from the perspective of horizontal integration. In Fig. 4, an arrow points from Jiangsu-Zhejiang to Guangxi, indicating the flow of industry factors between these two regions, meeting S5. Therefore, this geographic subject mind map meets 12 of the 13 criteria and covers all 6 dimensions of geographical synthetic thinking.

Geographic subject mind maps utilize the format of mind maps around the core of geographical thinking to provide students with a pattern for viewing problems from a geographical perspective. Considering that the correlation and synthesis of geography involve the connection and integration of factor systems, temporal changes, and spatial regions (Rediscovering Geography Committee and National Research Council, 1997), the geographic subject mind map proposed in this study is a model centred around geographic questions, unfolding the analysis and synthesis of geographic questions through factor, time, and space dimensions (see Fig. 3). Since factor, time, and space are the three dimensions of geographical synthetic thinking, the geographic

Table 1 Geographic subject mind map drawing standards.

Primary Indicator	Secondary Indicator	Requirements (Ideal Standard)
Q:Question	Q1 Question Description	Clearly, state the geographic question to be analysed
F: Factor	F1 Factor Angle	Analyse the issue from a factor perspective based on the situation in the question.
	F2 Representation of Factor System	Analyse the issue systematically from the perspectives of natural and human factors in the situation in the question.
	F3 Representation of Dominant Factors	Identify and list factors closely related to the problem, i.e., dominant factors, and analyse them based on this list.
	F4 Connection between Factors and Regions	Place factor analysis in the corresponding regions, or use lines or other methods to connect factors with regions.
	F5 Characterization of Factor interactions	If there is a relationship between factors, use unidirectional or bidirectional arrows (or brief text) to indicate factor interactions.
T: Time	T1 Static Time	Write down the time point(s) or static period(s) involved in the issue.
	T2 Expression of Temporal Changes in Geographical Phenomena or Influencing Factors	Determine whether geographic events or factors change over time in the problem; if not, just mention the time point, but if yes, use words/signs/timelines (nodes) to describe the changes.
S: Space	S1 Text of Regional Names	Write down the locations or regions involved in the geographic problem, phenomenon, or factor.
	S2 Indication of Multiple Regions	Determine whether the issue involves a single or multiple regions (consider whether dividing larger regions into smaller ones is necessary) and list all involved regions if there are multiple.
	S3 Characterization of Regional Differentiation	If multiple regions are compared, recognize or analyse regional differences from the perspective of regional differentiation (the differences between factors in different regions).
	S4 Representation of Intraregional Synthetic (Holistic) Characteristics	If it is necessary to analyse the integrity of the region, analyse and understand it from the perspective that factors are interacted to form a geo-environmental whole, and symbolize the whole formed by the synthesis of factors in the region.
	Representation of Interregional Synthetic (Regional Connections) Characteristics	If regional connections need to be analysed, identify which factors are responsible for the connections between regions, list these factors, and indicate the connections using arrows.

Note: The secondary indicators F2, F5, T2, S3, S4, and S5 correspond to the six dimensions of geographical synthetic thinking. The following geographic subject mind map teaching application standards (Table 3) focus on indicators reflecting the geographical synthetic thinking dimensions.

subject mind map possesses the inherent capacity to direct and develop geographical synthetic thinking.

Methodology

Research approach. After receiving training in the drawing standards of geographic subject mind maps and the application standards for its teaching, the teachers in the study carried out 4–5 classes in the experimental group according to the standard requirements. Before the experiment, the level of geographical synthetic thinking of the students was measured. During the experimental classes, the teachers applied the geographic subject mind maps in a standardized manner (striving to achieve an application level of 4.0 or above), and the level of geographical synthetic thinking of the students was measured again after the experiment to test whether there was a significant improvement. The study also examined whether there were differences in the improvement of students' geographical synthetic thinking skills due to the differences in the application of geographic subject mind maps by different experimental teachers.

Research procedure

Proposing research hypotheses. In the early stage of the research, the researchers sorted out the concept of geographical synthetic thinking and designed geographic subject mind maps using this perspective. They established drawing standards for geographic subject mind maps, creating a close internal relationship with the development of students' geographical synthetic thinking skills. At the same time, they set up application standards for teaching, which included determining the weights of the indicators through discussion among the core members of the project team (first author, second author, and corresponding author). The researcher discussed the importance of the eight indicators for evaluating the "geographic subject mind map application." Important indicators need to be assigned higher weights. The discussion among the three researchers focused on the importance of the indicators and the setting of the weights. This was based on each individual's subjective perception of the importance of each level of indicators relative to the previous level. They also discussed which weight calculation can more accurately represent the teacher's geographic subject mind map application level. After discussions and repeated adjustments, a consensus on the weight values was finally reached. The teaching application standards for the geographic subject mind map guide geography teachers in standardized teaching with geographic subject mind maps and thereby improve students' geographical synthetic thinking. This paper proposes the theoretical hypothesis that the application of standard geographic subject mind maps and standardized teaching can improve the level of students' geographical synthetic thinking.

Project experimental design. The project was designed to train geography teachers to learn how to draw geographic subject mind maps that meet the standards and to use them in a standardized way, thereby improving students' geographical synthetic thinking skills through the enhancement of these two factors; the theoretical hypothesis was then tested.

Ethical application and approval. The design documents and related ethical materials were submitted to the affiliated institution for ethical review. The approval letter from the institutional ethical review board was obtained on March 15, 2022.
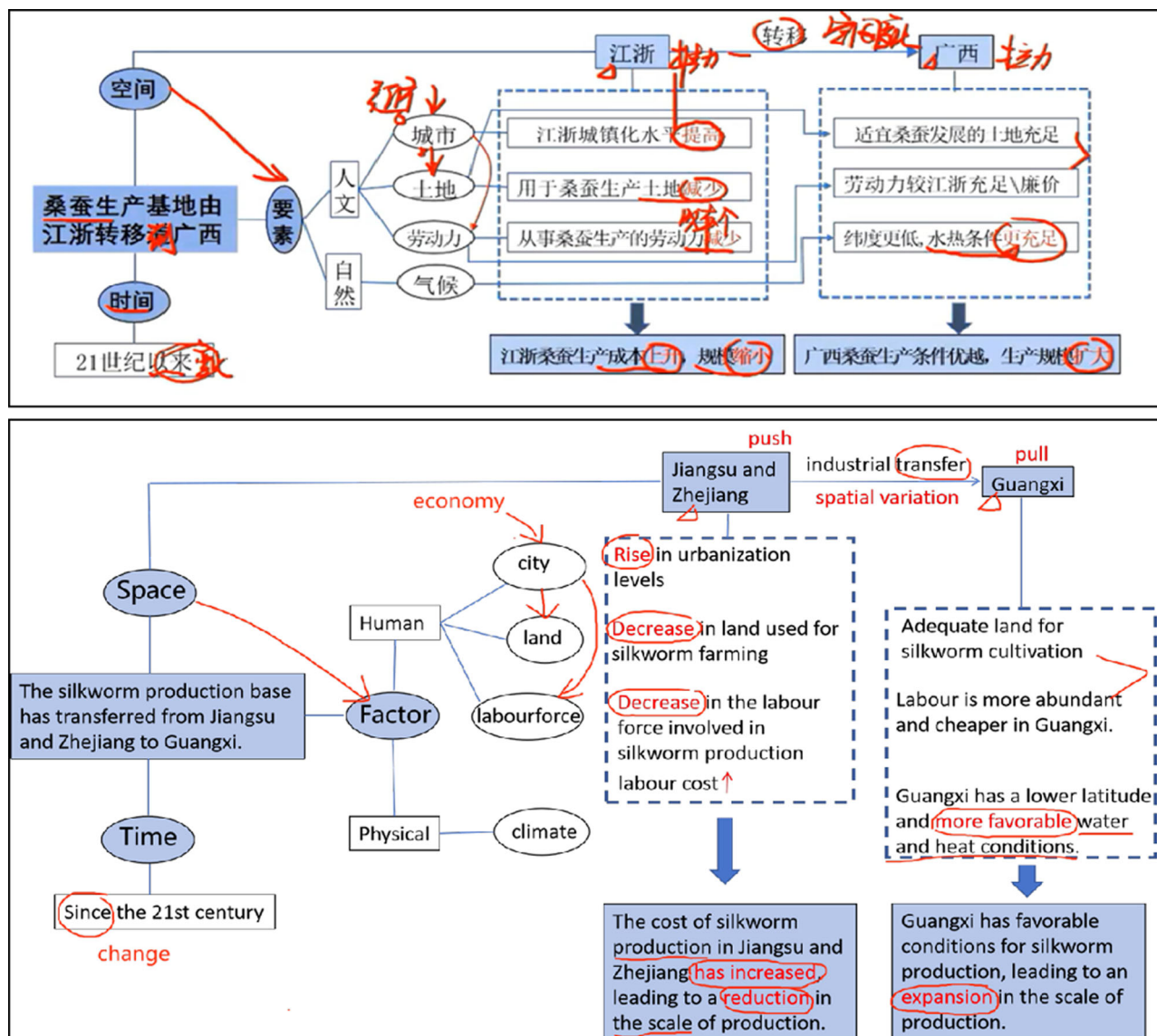
Fig. 4 Example of geographic subject mind map 1.

Pilot experiment. In June 2022, the first author (a working graduate student) recruited students from two classes at the high school where they worked to participate in the experiment, conducting preliminary experiments with 4 and 5 lessons. After achieving desirable hypothesis verification results in the experiment, the researchers decided to recruit a more extensive sample from various regions of China and continue to expand the scope of the experiment, after considering that the use of only one school and the limitations of conditions and design might make the validation of the results not universally applicable.

Development of experimental teacher training courses. Between July and August, the researchers developed systematic training courses based on the drawing standards for geographic subject mind maps and the application standards for its teaching. They then created a printed version for training experimental teachers during the expansion of the experiment.

Recruitment of experimental teachers. In August, experimental teachers were recruited from six regions across the country. After receiving approval from the high schools to conduct the

experiment, the relevant information about the experimental change was returned to the university ethics review committee.

Training of experimental teachers. On September 5, the experimental teachers received training on the two standards, aiming to teach the teachers how to draw geographic subject mind maps and how to apply them in a standardized manner during teaching. The training also introduced the student participant recruitment process and the experimental implementation process.

Recruitment of student participants. After September 5, the researchers recruited participants from the senior two and senior three students taught by the experimental teachers with their assistance. After the students and their parents signed informed consent forms (online version), the students officially became experiment participants.

Pretest before the experiment. Before the start of the experiment, a pretest was conducted on the participants to measure their level of geographical synthetic thinking. Due to the influence of the COVID-19 pandemic, the pretests in different experimental

schools were conducted at different times, with the earliest completed on September 14 and the latest on October 20.

Teaching design and approval. The six teachers needed to select and determine five experimental lessons and implement them intermittently from September to December 2022. Based on the teaching content of each class, the teachers needed to design the geographic subject mind maps used during the teaching process and set corresponding geographical synthetic thinking teaching objectives. One week before each class, the design plans were submitted to the core members of the project team (first author, second author, and corresponding author), who promptly provided suggestions for modifying and improving the geographic subject mind maps and teaching suggestions. After the final modification by the teachers and approval by the project team, the experimental classes could be officially conducted.

Teaching experiment. The teachers (T03-08) started the experiment sequentially on September 22. The COVID-19 pandemic made implementation of the experiment extremely difficult, and the forms of experimental classes very complicated, with some online, some offline, some hybrid with a portion of students online and the rest offline, and some with some students offline while the teacher and the remaining students were online. Eventually, 5 of the 6 teachers completed 5 classes, and another school completed 4 classes. The last class was completed on January 3, 2023.

Posttest. After the teaching experiments for each teacher were completed, the students' geographical synthetic thinking level was assessed. Posttests started on December 17, 2022, and the last school finished on January 6, 2023.

Organization of geographic subject mind maps and teaching design materials. Including the first author's preliminary experiments, a total of 38 lessons were taught. A total of 54 geographic subject mind maps were used in the experimental classes (30 lessons used one mind map, two lessons used two, four lessons used three, and two lessons used four). In February 2023, the first author extracted 54 geographic subject mind maps from the class videos or screen recordings of the 38 classes and randomly assigned them numbers. The dimensions of geographical synthetic thinking set in the teaching objectives of submitted lesson plans are also identified by teachers and recorded in the table. The drawing level of each geographic subject mind map is not evaluated separately here, but in the subsequent steps, the geographical synthetic thinking dimensions involved (A indicator) and the standard of mind map application (B indicator) are evaluated as units for each class and used to verify the hypothesis. Notably, the drawing level of geographic subject mind maps is not directly applied to test the hypothesis.

Evaluation of the A indicator (the involvement of geographical synthetic thinking dimensions) of the teachers' geographic subject mind map application. The core members of the project team (first author, second author, and corresponding author) invited two teachers (Zhu and Ma) who have experience in geographical synthetic thinking research. Together, they evaluated the level of the 54 geographic subject mind maps. The evaluation group held a mind map evaluation seminar on February 21st to understand the evaluation requirements. The evaluators independently identified the geographical synthetic thinking dimensions involved in the 54 geographic subject mind maps, finally confirming the dimensions covered by each mind map through discussion and eliminating inconsistencies. Then, according to the evaluation of the standards for teaching geographic subject

mind maps, the first author calculated the A1, A2, and A3 values of the A indicator for each teacher, with the final results verified and confirmed by the corresponding author.

Evaluation of the level of Indicator B (standardization of mind map application) in the application of geographic subject mind maps in teaching. Subsequently, the three core members of the project team separately watched the teaching videos of the experimental lessons and evaluated the standardization of the application of geographic subject mind maps by the teachers based on the B indicator (standardization of mind map application). The three members communicated and agreed on the evaluation results.

Calculate the weighted level of teachers' application of geographic subject mind maps. Based on the evaluation data, the first author calculated the final level of each teacher's application of geographic subject mind maps during the experiment.

Data analysis and model testing. Subsequently, an analysis is conducted of the teaching application level of geographic subject mind maps and the pretest and posttest geographical synthetic thinking level of their students, followed by further verification of the theoretical hypothesis.

Research sample. To obtain a more representative sample, this study selected participants from six major regions in China, including North China, South China, East China, Northeast China, Northwest China, and Southwest China, while considering the balance of participants from the three major economic zones of the eastern, central, and western parts of China. Finally, Shandong, Shanxi, Guangdong, Shanghai, Heilongjiang, Xinjiang, and Chongqing were chosen as seven representative provinces and cities to better represent China. A senior high school teacher of geography in senior high 2 or 3 was recruited from each province and city, and students from their classes were recruited to participate in the experiment. If a class was taught by a new teacher, there might be a unique improvement effect in geographical synthetic thinking. To avoid this effect, geography teachers who had been teaching the same students continuously until Grade 2 or Grade 3 were selected as participants. This is because the effect of a new teacher would have introduced a marginal effect after a period of teaching, and if the experiment produced an improvement, it would be the result of experimental factors.

The project team first established an information release platform for the study "Research on Students' Geographical Synthetic Thinking Cultivation Strategy and Effects Based on Geographic Subject Mind Maps" for the prerecruitment of teachers. Interested teachers could view the experimental content, process, requirements, and "Ethics Review Approval Letter" (with approval number: HR226-2022, see Supplementary Fig. S1 online) on the platform. After the teachers agreed to participate, the project team submitted a formal contact letter to the schools in the name of their institution, explaining the experimental details, and finally obtaining the schools' review and permission. After receiving approval letters from the schools (see Supplementary Figs. S2–S8 online), the teachers officially signed the informed consent form on the recruitment platform (https://www.wjx.cn/vm/eK4vMqn.aspx) and were confirmed as experimental teachers. The teachers then assisted in recruiting students, who checked the relevant information on the recruitment platform (https://www.wjx.cn/vm/tiAVJRx.aspx) and signed the "Student Informed Consent Form" if they wished to participate after consulting their parents. Parents also reviewed relevant

Table 2 Basic information of experimental teachers and student samples.

Class ID	T01	T02	T03	T04	T05	T06	T07	T08	Total Sample
Teacher Gender	Female	Female	Male	Female	Female	Male	Male	Male	
Teacher Education	Graduate	Graduate	Graduate	Bachelor	Graduate	Bachelor	Graduate	Bachelor	
Teaching Experience	7	7	7	21	4	20	5	10	
Student Grade	Senior 2	Senior 2	Senior 2	Senior 2	Senior 2	Senior 3	Senior 3	Senior 3	
Student Age	16–17	16–17	16–17	16–17	16–17	17–18	17–18	17–18	
Urban/ Rural	Rural	Rural	Urban	Rural	Urban	Urban	Urban	Urban	
Student Sample	47	55	38	33	32	32	21	43	301
Dropout Midway	6	8	0	3	3	3	2	9	34
Valid Sample	41	47	38	30	29	29	19	34	267
Gender: Male/ Female	28/13	25/22	8/30	10/20	13/16	3/26	4/15	7/27	98/169

(Note: The number of student participants identified as the "student sample" in the table is the number of students who signed the informed consent form and had valid pretest data, including students who fully participated in the experiment and those who dropped out halfway through).

information on the recruitment platform (https://www.wjx.cn/vm/thYWRxA.aspx) and signed the "Parent Informed Consent Form" if they agreed to have their child participate in the experiment. Students who agreed to participate were confirmed by the school, the students themselves, and their parents as approved for participation. The experimental classes in Guangdong Province were conducted by the first author, and recruitment was completed in June 2022. The recruitment of experimental teachers in the other six provinces was completed by the end of August 2022, and students were recruited in September 2022. The basic information of the seven experimental teachers and their 301 recruited students can be found in Table 2. Due to the impact of the pandemic and students' personal factors, 34 students dropped out of the experiment or failed to complete the posttest, leaving 267 valid student participants in the sample. Reasons for student withdrawal included calling in sick, changing courses (currently, geography is an elective in the sophomore and junior grades in China), and failing to answer objectivity identification items. In the analysis, teacher and student identities were anonymized to protect their privacy.

Teachers understanding of geographic subject mind maps. Although this study provided standards for geographic subject mind maps (see Table 1) and offered unified training for teachers, teachers may have designed their mind maps based on their instructional requirements, influenced by their understanding of these standards. Figures 4–6 in the article display the mind maps used in the classroom by three different teachers. The variations in their mind map styles and differences in meeting the standard (see Table 3) highlight the teachers' diverse understandings of the geographic subject mind map standard.

Unlike the geographic subject mind map example 1 (Fig. 4) and example 2 (Fig. 5), example 3 (Fig. 6) does not specify the question to be analysed, not meeting Q1. Considering physical and human factors for analysis, it lists climate, vegetation, and soil, meeting F1, F2, and F3; some factors are written next to "alluvial fan", and some are written next to "hillside", meeting F4. Arrows indicate the connection between factors, such as pointing from "landform" to "climate", meeting F5; in terms of time, it indicates "winter-spring", meeting T1, but no expression of geographic phenomena or factors changing over time is included, not meeting T2. It has "alluvial fan" and "hillside" as two spatial

locations, meeting S1 and S2, but it neither analyses regional differences from the perspective of factor differences (S3) nor synthesizes the interactions and influences of these factors to derive the overall characteristics of the regions (S4). It does not indicate the flow of factors between regions, leading to regional connections, not meeting S5. Therefore, this geographic subject mind map meets 7 of the 13 criteria and can teach only two geographical synthetic thinking dimensions: geographical factor system thinking and geographical factor interaction thinking.

Geographic subject mind maps in class. The application of geographic subject mind maps in teaching involves designing a geographic subject mind map that meets the drawing standards in the experimental course and achieving the objectives for cultivating students' geographical synthetic thinking on six dimensions by using it according to the application norms. The application standards of geographic subject mind map teaching were developed (see Table 4), which are divided into A. involvement of geographical synthetic thinking dimensions and B. regulations of geographic subject mind map application. The A indicators are specifically divided as follows: A1, dimension frequency; A2, dimension coverage; and A3, dimension goal implementation degree. The B indicators are specifically divided as follows: B1, introduction of geographic subject mind map drawing standards; B2, analysing problems based on the geographic subject mind map; B3, guiding students to draw mind maps; B4, displaying teacher-drawn mind maps to students; and B5, guiding students to modify and improve mind maps. The design rationale of these indicators is as follows: First, the geographic subject mind map can precisely represent the six dimensions of geographical synthetic thinking, and the use process can enhance recognition of these six dimensions, allow internalization into metacognition, and thus improve the overall level of students' geographical synthetic thinking. Therefore, the frequency (A1), coverage (A2), and realization of objectives in each class (A3) of the dimensions of geographical synthetic thinking in the geographic subject mind maps used in this course are all important factors affecting the effectiveness of teaching geographical synthetic thinking. Second, metacognition as a knowledge of learning methods is teachable, and teachers' standardized use of geographic subject mind maps in class can enhance students' cognition and metacognition, thus improving

Table 3 The application standards for teaching geographic subject mind maps.

| Primary Indicator	Weight	Secondary indicator	Weight	Indicator connotation	Evaluation method (5-point scale)	Weighted score
A: Involvement of Geographical Synthetic Thinking Dimensions	0.65	A1 Frequency of Geographical Synthetic Thinking Dimensions	0.19	The number of geographical synthetic thinking dimensions involved in the mind maps used in each experimental class (one or more maps), and the total number of geographical synthetic thinking dimensions involved in all experimental classes, divided by 6 and then by the number of classes to get the average frequency of occurrence of each dimension in each class.	Average frequency * 5	0.1235
		A2 Coverage of Geographical Synthetic Thinking Dimensions	0.54	The coverage of the 6 dimensions of geographical synthetic thinking by all geographic subject mind maps used in multiple classes during the experiment.	The cumulative number of dimensions covered by all experimental classes/6 * 5 (excluding the number of coverage times)	0.351
		A3 Implementation Degree of Geographical Synthetic Thinking Objectives	0.27	The implementation of the preset geographical synthetic thinking objectives in the process of using geographical subject mind maps in teaching.	5 points * implementation ratio, with 100% implementation being 5 points	0.1755
B Standardization of Mind Map Applications	0.35	B1 Introduction to Geographical Subject Mind Map Drawing Standards	0.15	The teacher prints out the geographical subject mind map pattern and drawing standards and distributes them to the students, introducing its function and the requirements for drawing standard geographical subject mind maps to the students.	Scan through the experimental classes, score 0 or 1 according to the compliance, and calculate the score using the compliance level * 5	0.0525
		B2 Analysing Problems Based on Geographical Subject Mind Maps	0.25	In teaching, the teacher can analyse and solve geographical problems based on the geographical subject mind maps drawn by students and themselves.	Scan through the experimental classes, score 0 or 1 according to the compliance level, and calculate the score using the compliance level * 5	0.0875
		B3 Guiding Students to Draw Mind Maps	0.21	When analysing geographical problems, the teacher first asks students to draw geographical subject mind maps based on the problem's attributes and use them to analyse the problem.	Scan through the experimental classes, score 0 or 1 according to the compliance level, and calculate the score using the compliance level * 5	0.0735
		B4 Showcasing Teacher-Drawn Mind Maps to Students	0.24	After students draw their geographical subject mind maps, the teacher provides a standard geographical subject mind map drawn by themselves and uses it to analyse the problem more accurately.	Scan through the experimental classes, score 0 or 1 according to the compliance level, and calculate the score using the compliance level * 5	0.0840
		B5 Guiding Students to Revise and Improve Mind Maps	0.15	The teacher can organize students to compare their own geographical subject mind maps with the standard ones, identify the deficiencies in their own maps, and ask students to revise and improve them.	Scan through the experimental classes, score 0 or 1 according to the compliance level, and calculate the score using the compliance level * 5	0.0525
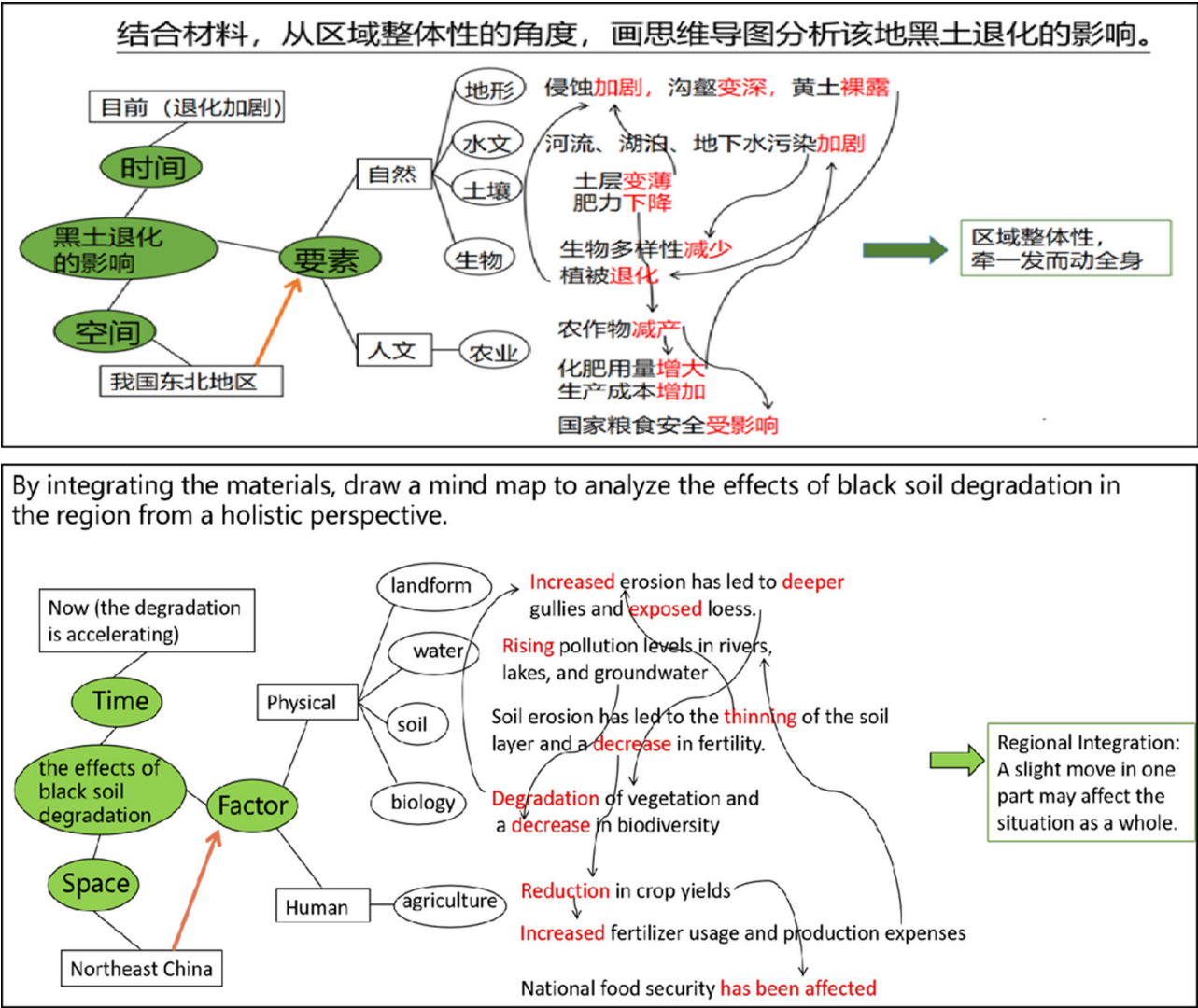
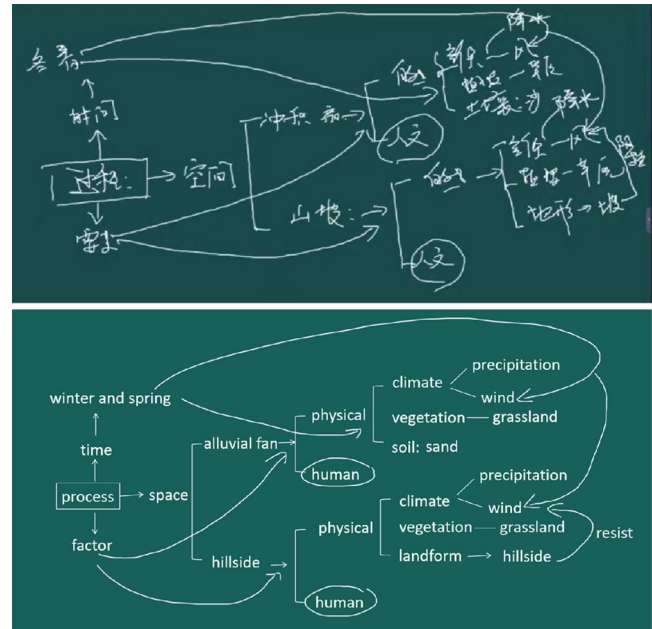**Fig. 5 Example of geographic subject mind map 2.**

Fig. 6 Example of geographic subject mind map 3.

students' geographical synthetic thinking skills. For example, teachers can teach students core knowledge by introducing the drawing standards of geographic subject mind maps (B1), relying on geographic subject mind maps to analyse problems (B2), guiding students to draw mind maps (B3), displaying teacher-drawn mind maps to students (B4), and guiding students to modify and improve mind maps (B5) so that students know when and how to use geographical synthetic thinking to solve geographical problems. These methods can also promote students' metacognition of geographical synthetic thinking through practice. The first, second, and corresponding authors have determined the weights of these eight indicators through discussion (see Table 4). In summary, the application and evaluation criteria of geographic subject mind maps can guide teachers in their use in class and evaluate their application, thereby studying the relationship between the use of geographic subject mind maps in teaching and the improvements in students' geographical synthetic thinking to verify whether the research hypothesis is valid.

Results

Teachers understanding of geographic subject mind maps. A total of 38 lessons were taught in the eight experimental classes of this study, and 54 geographic subject mind maps were used in the

Table 4 Drawing level of 3 geographic subject mind maps.

Primary Indicator	Secondary Indicator	Fig. 4	Fig. 5	Fig. 6
Q Question	1. Q1 Question Description	Conforms	Conforms	Nonconforming
F Factors	2. F1 Factor Angle	Conforms	Conforms	Conforms
	3. F2 Representation of Factor System	Conforms	Conforms	Conforms
	4. F3 Representation of Dominant Factors	Conforms	Conforms	Conforms
	5. F4 Connection between Factors and Regions	Conforms	Conforms	Conforms
	6. F5 Characterization of Factor Interactions	Conforms	Conforms	Nonconforming
T Time	7. T1 Static Time	Nonconforming	Nonconforming	Conforms
	8. T2 Expression of Time Changes in Geographical Phenomena or Influencing Factors	Conforms	Conforms	Nonconforming
S Space	9. S1 Text of Regional Names	Conforms	Conforms	Conforms
	10. S2 Indication of Multiple Regions	Conforms	Nonconforming	Conforms
	11. S3 Characterization of Regional Differentiation	Conforms	Nonconforming	Nonconforming
	12. S4 Representation of Intraregional Synthetic (Holistic) Characteristics	Conforms	Conforms	Nonconforming
	13. Representation of Interregional Synthetic (Regional Connections) Characteristics	Conforms	Nonconforming	Nonconforming
Drawing level of Geographic Subject Mind Maps (Degree of Conformity)		12/13	9/13	7/13

experimental classes (see Supplementary Table S4 online). Figures 4–6 in the article display the geographic subject mind maps drawn and used by the experimental teachers in their classes. The following is an example of the evaluation of these three diagrams in terms of meeting the criteria for drawing mind maps in the subject of geography, and the results are shown in Table 3.

Geographic subject mind maps in class and their effectiveness. What is the level of teachers' application of geographic subject mind map during the experiment? Evaluating the experimental lessons of the eight experimental classes, weighting and summarizing them.The weighted score of the summary evaluation of the application of the geographic subject mind maps is 4.30 points (>4.0), of which Indicator A, "Involvement of Geographical Synthetic Thinking Dimension," in the application of the geographic subject mind maps is 4.07 points, and Indicator B, "Standardization of Mind Map Application," is 4.72 points. This indicates that the improvement of the independent variable in the teaching experiment met the experimental requirements. In the experiment, the average level of geographical synthetic thinking of the 267 valid student participants increased from 64.87 points in the pretest to 75.38 points in the posttest, with an increase of 10.51 points and an improvement rate of 16.20%. The improvement effect is significant. The difference between pretest and posttest data was tested for a normal distribution, and with the help of histograms and Q–Q plots, the difference was approximately normally distributed, meeting the conditions for using a paired sample T-test. The P-value for the paired sample T-test is $0.000 < 0.01$, indicating an extremely significant difference between the pretest and posttest levels. Specific indicator scores are shown in the "overall" category in Table 5. This validates the hypothesis that the standardized use of geographic subject mind maps can significantly improve students' geographical synthetic thinking level.

Furthermore, the posttest levels of the students' six dimensions of geographical synthetic thinking were all higher than the pretest levels, and the differences all reached significant levels (see Table 6). This indicates that the actual experiment not only improved the overall geographical synthetic thinking level of the sample but also improved the level of all dimensions of it without exception. Thus, it further demonstrates the correctness of the hypothesis from a more detailed perspective.

For each geographic subject mind map by the teachers, statistics were measured on the dimensions of geographical synthetic thinking (see the Supplementary Tables S1, S2, S4 for

the detailed statistical process data), and the scores of the three subindicators in Indicator A (involvement of geographical synthetic thinking dimension) and the five subindicators in Indicator B (standardization of mind map application) were calculated for each class of the experimental teachers. The final scores of the application level for each teacher's geographic subject mind maps are obtained, and the calculation results are shown in the T01-T08 column data in Table 5. To analyse the relationship between the improvement of students' geographical synthetic thinking and the level of teachers' application of geographic subject mind maps, SPSS 26.0 was used to calculate the mean scores and improvement scores between pretest and posttest data of geographical synthetic thinking levels for the eight experimental classes (see Table 5). The data on the teaching application of geographic subject mind maps for the eight experimental classes and the improvement scores of students' geographical synthetic thinking level were subjected to normality tests. Based on the P-value of normality tests (W-test $P = 0.326 > 0.05$ for teaching application, W-test $P = 0.809 > 0.05$ for students' improvement scores), as well as the assessment of histograms and other tools, both meet the conditions for the Pearson correlation analysis. A correlation analysis between the two reveals a significant positive relationship between the level of the application of the geographic subject mind map and the improvement in students' geographical synthetic thinking, with $p = 0.043 < 0.05$ and an effect size $r = 0.722$. This reflects the significant role of the application of geographic subject mind maps in the development of students' geographical synthetic thinking, thus validating the hypothesis that the terms of application affect student improvements.

Discussion
Why can the use of a geographic subject mind map effectively improve students' geographical synthetic thinking level? This empirical study aims to verify the hypothesis that using a geographic subject mind map in a standardized and consistent manner in teaching can effectively improve students' geographical synthetic thinking skills. First, a geographic subject mind map is a visualization tool for analysing geographical issues. Mind maps or concept maps can help students visualize analytical thinking (Jones, 2015). Past research has also shown that the use of specific visualization tools in geography classrooms has a positive effect on developing geographical systems thinking (Cox et al. 2020), which is essentially similar to geographical synthetic thinking. Second, the geographic subject mind map used in the

Table 5 Scores for the application of teachers' geographic subject mind maps teaching.

Teacher and Class		Overall	T01	T02	T03	T04	T05	T06	T07	T08
Total use of mind maps in experimental class		54	12	12	5	5	4	5	5	6
Total experimental class hours		38	4	5	5	5	4	5	5	5
A1 Score of GST dimension frequency		2.82	3.54	3.33	2.67	2.50	2.50	1.67	2.83	3.83
A2 Score of GST dimension coverage		4.48	5.00	5.00	5.00	5.00	4.17	2.50	4.17	5.00
A3 Score of GST dimension target implementation		4.13	5.00	5.00	3.80	3.67	4.19	2.92	4.00	4.43
B1 Introduction to the drawing standard of GSMM		3.75	5.00	5.00	5.00	0	0	5.00	5.00	5.00
B2 Analysis of problems based on GSMM		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
B3 Guiding students to draw GSMM		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
B4 Showing the teacher's own GSMM to students		5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00	5.00
B5 Guiding students to revise and perfect their GSMM		4.38	0	5.00	5.00	5.00	5.00	5.00	5.00	5.00
A Involvement of GST dimension		4.07	4.72	4.68	4.23	4.17	3.86	2.45	3.87	4.63
B Standard application of GSMM		4.72	4.25	5.00	5.00	4.25	4.25	5.00	5.00	5.00
Level of GSMM teaching application		4.30	4.56	4.79	4.50	4.19	3.99	3.35	4.26	4.76
Number of student samples		267	41	47	38	30	29	29	19	34
Pretest of GST	Mean	64.87	61.22	63.94	54.47	66.75	69.74	72.76	70.96	66.25
	SD	10.64	10.64	10.36	11.17	8.06	8.42	8.46	6.02	6.55
Posttest of GST	Mean	75.38	68.82	75.46	75.33	76.83	78.48	72.27	78.16	80.42
	SD	10.01	9.24	8.08	12.10	10.67	9.05	10.10	7.30	7.85
Improvement score		10.51***	7.60***	11.52***	20.86***	10.08***	8.74**	−0.49	7.20**	14.17***
Standard deviation		11.27	9.33	8.63	13.01	9.32	12.07	8.17	7.57	8.48
Increase ratio		16.20%	12.41%	18.02%	38.30%	15.10%	12.53%	−0.67%	10.15%	21.39%
Significance (two-tailed)		0.000	0.000	0.000	0.000	0.000	0.001	0.75	0.001	0.000

Note: Both pretest and posttest scores are on a 100-point scale (same below). The pretest and posttest differences in the geographical synthetic thinking level for all eight class sections and the overall sample were tested for a normal distribution. Through the P-value of the W-test and tools such as histograms, the differences all follow a normal or approximately normal distribution, meeting the requirements for using paired sample T-tests.
**P < 0.01, ***P < 0.001.

Table 6 Pretest and posttest data of geographical synthetic thinking dimensions and paired sample t-test.

Dimension		Geographical factors system thinking	Geographical factors interaction thinking	Regional differentiation thinking	Temporal changes thinking,	Intraregional synthetic thinking	Interregional synthetic thinking	Geographical Synthetic Thinking
Pretest	Mean	70.02	64.76	67.34	64.19	58.31	64.61	64.87
	SD	12.96	12.69	13.63	15.41	12.66	13.87	10.64
Posttest	Mean	82.68	76.42	76.61	73.15	69.36	74.06	75.38
	SD	10.79	12.41	12.30	12.31	12.34	11.99	10.01
Increase ratio		18.08%	18.00%	13.77%	13.96%	18.95%	14.63%	16.20%
Significance (two-tailed)		0.000	0.000	0.000	0.000	0.000	0.000	0.000

Note: The pretest and posttest differences in each dimension of geographical synthetic thinking have been tested for a normal distribution, and with the help of histograms, the differences are all approximately normally distributed, meeting the conditions for the use of paired sample *T*-tests.

study is a thinking framework that helps students consider geographical issues. When solving geographical problems, students need more assistance and structure to construct connections among the items of information they encounter (Hmelo-Silver and Azevedo, 2006; Osvaldo Muñiz Solari et al. 2015), much like geographers often need conceptual framework diagrams to help analyse problems (Favier and van der Schee, 2014). Third, as York et al. argue, to promote effective student learning with systems thinking approaches, teachers must provide scaffolded and guided systems-thinking activities for students (York et al. 2019). In the experiment, teachers helped students create and refine their geographic subject mind maps, providing guidance for analysing geographical questions in terms of time, space, and factors, thus providing scaffolds for the development of geographical synthetic thinking. Fourth, the geographic subject mind map used in the experiment is a thinking framework that displays the process of geographical synthetic thinking. Its repeated use has helped students develop a habit of looking at issues from a geographical perspective and conducting research using an integrated approach in geography. This "habit" is a metacognitive thinking pattern applied by students when dealing with complex systems (Mehren et al. 2018), which is an essential factor in improving geographical synthetic thinking (Zhu, 2018; Fan et al. 2020; Mehren and Rempfler, 2022). To achieve effective and lasting results, geographical synthetic thinking must be internalized as a metacognitive tool (Ben-Zvi-Assaraf and Orion, 2010; Gilissen et al. 2020). Therefore, on one hand, the use of geographic subject mind maps has improved students' metacognitive recognition of geographical synthetic thinking, enabling them to better understand how to engage in geographical synthetic thinking and apply it to geographical problems, thus raising their geographical synthetic thinking skills. On the other hand, in this study, teacher training enhanced teachers' awareness of teaching geographical synthetic thinking. The increased awareness of teaching among teachers has resulted in teaching behaviours that use geographic subject mind maps for instruction. Consequently, these teaching behaviours promoted the development of students' geographical synthetic thinking.

Why is there a positive correlation between the teaching application of geographic subject mind maps and the improvement in students' geographical synthetic thinking? First, this conclusion is the result of statistical data analysis. Despite having only eight classes, the observed trend remains very apparent. For instance, the levels of application of the geographic subject mind map in teaching for Classes T03, T04, and T05 were 4.50, 4.19, and 3.99 points, respectively, and the improvements in their students' geographical synthetic thinking were 20.86, 10.08, and 8.74, respectively. Even though the pretest scores of these three classes were from low to high, the degree of improvement

has brought the levels of the three classes closer together, which to some extent, demonstrates the existence of a relationship between the independent and dependent variables. The correlation analysis of data from 8 groups also shows that the level of application of the geographic subject mind map in teaching by teachers is positively related to the enhancement of students' geographic synthetic thinking.

Secondly, among the 8 experimental classes, there was a special case, Secondly, among the 8 experimental classes, there was a special case, indicating that the improvement of geographical synthetic thinking level requires the standardized application of the geographic subject mind map. The geographical synthetic thinking level of students in the T06 experimental class did not improve. The scores on the three A indicators (involvement of geographical synthetic thinking dimension) of T06 were lower than those of other experimental classes, resulting in a lower application of geographic subject mind maps in teaching than in other experimental classes (see Table 5). T06's geographic subject mind map application did not meet the basic requirement of a 4.0 level, which affected the improvement of the geographical synthetic thinking level of the class. For instance, its A2 indicator (coverage of geographical synthetic thinking dimensions) scored 2.5 points (out of 5), meaning three of the six geographical synthetic thinking dimensions were not covered in the experiment, affecting the overall improvement effect of geographical synthetic thinking. Its A3 indicator (the implementation degree of geographical synthetic thinking objectives) scored 2.92 points (out of 5), indicating that the geographic subject mind map used in the classroom could achieve only 58.4% of the expected teaching goals for geographical synthetic thinking. A large proportion of geographical synthetic thinking objectives were not realized during the teaching process. This case shows that students' geographical synthetic thinking skills can be effectively improved only when geographic subject mind maps are applied with proper standards in teaching. In the analysis, the researchers doubted the accuracy of the posttest data from the T06 class and retested the students online 50 days after the end of the teaching experiment (after a 40 day winter holiday). The results of the retest data were highly consistent with the posttest data, with a correlation coefficient of 0.671, which was significant at $p = 0.000 < 0.01$ (see the Supplementary Table S3), indicating that the posttest data were accurate and reflected the high retest reliability of the measuring tools. The experiment indirectly suggests that the improvement of students' geographical synthetic thinking skills is slow under natural conditions without geographic subject mind map teaching interventions. It also supports the argument that experiments are an effective way to quickly improve students' geographical synthetic thinking level. This conclusion is consistent with the empirical research results of Kali et al.: students do not develop systems thinking skills by

participating in unguided systems-thinking activities or by learning systems or systems concepts (Kali et al. 2003).

Lastly, interviews with experimental teachers corroborate the experimental data. After the teaching experiment, in an interview with the experimental teacher T05, it was mentioned, "Among the two classes I taught simultaneously, the one not involved in the experiment did not use the geographic subject mind map. In classroom teaching, when asking the same question, compared to the other class, students in the experimental class exhibited a higher level of improved synthetic thinking." Although this study did not recruit such classes as a control group, the interviews with the experimental teachers reveal that teaching with the geographic subject mind map has a significant impact on students' synthetic thinking.

Does teacher training lead to better teaching and learning outcomes? This study found differences in the application level of geographic subject mind maps in teaching among teachers from different experimental groups, with varying experimental outcomes.

For instance, the pretest data for T03 was the lowest. However, the level of application of the geographic subject mind map of their teacher was high, scoring 4.50 out of 5. This resulted in the greatest improvement in students' geographical synthetic thinking. On one hand, the teacher's understanding of and standardized use of the geographic subject mind map enhanced students' understanding, thereby improving students' level of geographical synthetic thinking. On the other hand, although the T03 pretest scores were far below the average, the development of geographical synthetic thinking did occur within the Zone of Proximal Development (Vygotsky, 1978). For students with weaker geographical synthetic thinking abilities, geographic subject mind maps teach them methods of synthetic thinking, acting as a scaffold that connects their current level of development with their potential level of development. It is the "subject content knowledge" that they greatly need and are capable of learning; hence, they made significant progress. Therefore, the rapid improvement of T03 was not only influenced by the teacher's independent variable but also guaranteed by the Zone of Proximal Development theory. This suggests that within the students' Zone of Proximal Development, increased effort from a teacher can lead to optimal and significant outcomes.

In contrast, the pretest data of T06 was the highest, but there was no further improvement after the experiment, and the posttest data did not rank the highest among the 8 experimental groups. For T06, it is true that the students' geographical synthetic thinking had already developed well even without the tool. However, the T07 class had similarly high levels of geographical synthetic thinking as the T06 in the pretest, with scores of 72.76 and 70.96, respectively. Meanwhile, their teachers' levels of application of the geographic subject mind map in teaching were 3.35 and 4.26, respectively. Due to the high independent variable level of T07 class, the students' final level of geographical synthetic thinking reached 78.16 points, surpassing the stagnant T06 class (posttest 72.27). This also demonstrates the effect of the independent variable on the dependent variable.

Additionally, within the teaching application standards for the geographic subject mind map, there are differences in the weights of various indicators, indicating they have different effects on teaching effectiveness. T04 and T05 scored zero points on the indicator B1 (introducing the geographic subject mind map to students) because the experimental teachers did not explain the geographic subject mind map's drawing standards item by item to the students at the beginning of the first experimental lesson as required. However, this did not significantly affect the

experimental results, with T04 and T05 showing noticeable improvement. In fact, before the experimental class, the project team had already distributed the geographic subject mind map's drawing standards to the students. A formal explanation by the teachers might have helped the students pay more attention to or understand the geographic subject mind map's drawing standards. Yet, bypassing this step and directly using cases for teaching the geographic subject mind map could also achieve good results. This outcome might be due to two reasons. On one hand, for students with a good learning foundation and autonomous learning abilities (pre-test data of T04 and T05 students exceeded the average level), it might not be necessary to teach abstract models, as using examples based on these models would be sufficient for students to understand the method of thinking about problems through geographical synthetic thinking. On the other hand, in the teaching application standards, different teaching phases corresponding to different indicators might vary in importance for the cultivation of geographical synthetic thinking. Within the system of indicators for the teaching application standards, the weight of the B1 indicator is relatively low (0.35 * 0.15). If other important indicators are well executed, such as in T04 and T05, satisfactory teaching outcomes can similarly be achieved.

Conclusion
The following conclusions are drawn from this study: teachers' standardized use of geographic subject mind maps can significantly improve students' geographical synthetic thinking skills and has a significant improvement effect on various dimensions of geographical synthetic thinking. The level of application of geographic subject mind maps in teaching has a significantly positive correlation with the increase in students' geographical synthetic thinking levels.

Standardized use of geographic subject mind maps includes involving most geographical synthetic thinking dimensions and using mind maps according to requirements. The former involves the more frequent occurrence of geographical synthetic thinking dimensions, greater coverage of synthetic thinking dimensions, and better implementation of preset geographical synthetic thinking dimension targets. The latter includes introducing geographic subject mind map drawing standards, analysing problems based on geographic subject mind maps, guiding students in drawing mind maps, displaying teacher-drawn mind maps to students, and guiding students in revising and improving mind maps. Based on the above conclusions, this paper suggests that to improve students' geographical synthetic thinking skills, teachers make full use of geographical issues with comprehensive characteristics for teaching geographic subject mind maps. The coverage and frequency of geographical synthetic thinking dimensions in teaching design should be ensured, and standardized geographic subject mind maps should be used for teaching activities.

In this research, the training sessions have enabled teachers to realize that developing a specific skill or mindset in students requires both educational theory support and assistance from educational technology. This, in turn, enhances teachers' understanding of scientific education. The two standards provided by this experiment ("Geographic Subject Mind Map Drawing Standard" and "The Application Standards of the Geographic Subject Mind Map Teaching") have empowered experimental teachers with the skills to foster students' development of geographical synthetic thinking. Through specialized teaching supported by technology, students' learning and training become more scientifically oriented, thereby efficiently achieving teaching objectives.

However, teaching geographical synthetic thinking is a complex system. Factors such as teachers' understanding of the

geographic subject mind map, teachers' research or teaching experience in synthetic thinking, the existing knowledge of students, and students' learning abilities will all affect the outcome of the experiment. The impact of the subject mind maps on students' geographical synthetic thinking, both directly and indirectly, is a topic worthy of investigation. Therefore, it is still very necessary to conduct follow-up research, such as adding control groups, increasing controlled variables, and expanding the sample size. It is hoped that the conclusions and discussions of this study will encourage geography teachers to more effectively cultivate students' geographical synthetic thinking.

Data availability

All data generated or analyzed during this study are included in this article and its supplementary file.

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Author contributions

The authors confirm their contributions to the paper as follows: Xiaoxu Lu determined the research approach, conducted the overall experiment design, and managed the experiment process. Zhijie Huang assisted in defining research ideas and experimental designs, executing research plans, conducting teacher training, performing teaching experiments, analyzing data, and writing research manuscripts. Ye Yang participated in experimental design, assisted in teacher training, helped analyze data, and contributed to writing papers. Lirong Dong, Aimin Gao, Zhenyu Guo, Jiasheng Wang, Xia Zhang, and Yuanpeng Zhao assisted in sample recruitment, designed mind maps for use in teaching experiments following the geographic subject mind map drawing standards, and conducted experiments based on the geographic subject mind map teaching application standards. They also administered pretests and posttests to assess students' geographical synthetic thinking levels.

Competing interests

The authors declare no competing interests.

Ethical approval

As per ethical principles for involving human participants to serve our research purpose, we have collected primary data including written Questionnaire with the permission and supervision of cooperating schools, and the University Committee on Human Research Protection of East China Normal University (Approval No.: HR 226-2022). We also obtained informed consent from the teachers and students who participated in the experiment, and the students' parents and all research was performed in accordance with relevant guidelines.

Informed consent

Informed consent was obtained from all the participants.

Additional information

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