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Validation and Use of the Comprehensive Scientific Creativity Assessment (C-SCA) Instrument for Secondary School Students

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ABSTRACT

This study evaluates the reliability and validity of the Comprehensive Scientific Creativity Assessment (C-SCA) instrument by implementing necessary modifications, extending the sample size, and providing a clear and objective scoring process. A total of 347 participants from a secondary school in China completed two scientific creativity assessments, using the two versions of the C-SCA. The results indicate acceptable reliability and validity for both versions. Descriptive analyses revealed that males and only children (those with no siblings) performed better in scientific knowledge, while children from affluent backgrounds exhibited higher intrinsic motivation in scientific creativity. However, no significant demographic differences were observed in divergent or convergent thinking performance. Scientific knowledge scores varied significantly according to the educational level and occupation of students' mothers. This study also found that divergent and convergent thinking mutually promoted each other, while extrinsic motivation negatively affected divergent thinking and scientific knowledge enhanced convergent thinking. This research offers valuable insights into scientific creativity assessment by validating the C-SCA and proposing a clear scoring process. By investigating the impact of demographic variations on scientific creativity and elucidating the relationships among the components of scientific creativity, the study provides educators with practical recommendations for fostering creativity in science education.

Introduction

Creativity is a key competence that supports individuals and groups to achieve better outcomes and can drive forward human culture and society in diverse areas (Guilford, 1950; OECD, 2023a). Within science education, scientific creativity can be applied when conducting science experiments, solving science problems, and completing science activities in a scientific manner (Hernández-Torrano & Ibrayeva, 2020). Students exhibiting high levels of scientific creativity are more capable of innovative problem-solving, generating novel discoveries, and advancing academic progress (Ramly et al., 2022). Notably, scientific creativity, unlike other forms of creativity, must align with the framework of scientific knowledge (W. Hu & Adey, 2002), requiring logical reasoning or strict empirical testing (Kind & Kind, 2007). Accordingly, Xu et al. (2024) define scientific creativity not only as inspiration and imagination but also as the transformation of creative ideas into scientific knowledge through logical reasoning within the existing intellectual framework of the discipline.

Helping students unleash their scientific creativity is an important aspect of science education, and one that should be supported by valid assessment (Hong et al., 2022). A number of instruments measure scientific creativity by focusing on divergent thinking, such as the "Scientific Creativity Test (SCT)" (W. Hu & Adey, 2002) and the "Creative Scientific Ability Test" (C-SAT) (Sak & Ayas, 2013). Some researchers also recognize the importance of convergent thinking and have incorporated this into their assessments (de Vries & Lubart, 2019; Yang et al., 2019). Beyond these types of thinking, components such as motivation (Agnoli et al., 2016; Taylor & Kaufman, 2021) and personality (Kaufman et al., 2010; Roth et al., 2022) have also been considered. Given the multidimensional nature of scientific creativity, some researchers have adopted a comprehensive approach to its measurement (Agnoli et al., 2016; Xu et al., 2024). For instance, the "Comprehensive Scientific Creativity Assessment (C-SCA)" developed by Xu et al. (2024) manifests such an approach, although they suggest further modification of their instrument. In addition, Xu et al. (2024)

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emphasized the categorization and time-consuming issues that arise when scoring divergent thinking tasks, concerns echoed in other studies (R. E. Beaty & Johnson, 2021; Rietzschel et al., 2024). Consequently, more research is needed to address the challenges in the scoring process for scientific creativity.

Demographic variables have also been a topic of interest in scientific creativity research, as they may influence students' performance in various assessments. Studies exploring general science examinations have found that student performance often varies by gender (Shao & Pang, 2016; Voyer & Voyer, 2014) or family background (J. Liu et al., 2020; Morgan et al., 2016). Regarding motivation, evidence suggests that males are generally more motivated to learn science than females (Potvin & Hasni, 2014), and children with more educated parents tend to show greater confidence and interest in science (Steinmayr et al., 2012). Divergent thinking is also a key measure of scientific creativity, yet research findings on gender differences in this area remain inconsistent (W. Hu et al., 2004; Xu et al., 2024). For instance, W. Hu et al. (2004) found that Chinese males exhibited superior divergent thinking abilities compared to females. Conversely, Xu et al. (2024) found no significant gender differences in divergent thinking scores, but noted that females outperformed males in convergent thinking. There is a paucity of empirical research examining family background differences in divergent or convergent thinking within scientific creativity assessments (Dai et al., 2012). Using a comprehensive scientific creativity assessment instrument, it is therefore worth exploring whether demographic variables, such as gender and family background, influence students' scientific creativity.

Another concern for researchers is the relationships among the components of scientific creativity (Agnoli et al., 2016; Wang et al., 2021; Xu et al., 2024). In terms of scientific knowledge, extensive domain expertise in adults might lead to cognitive inflexibility, as prior knowledge shapes their mental representations of problems, prompting them to rely on familiar solutions (Acar & Van Den Ende, 2016). However, research in K-12 education has yielded different findings. For instance, Ayas and Sak (2014) found a positive correlation between sixth-grade students' scientific knowledge and their performance in scientific creativity tasks, as measured by science examination scores and the C-SAT instrument. Similarly, W. Hu and Adey (2002) found that as Chinese students aged and gained more scientific knowledge, their performance in scientific creativity tests, as measured by the SCT, also improved. Additionally, divergent thinking, focusing on diversity, and convergent thinking, aiming for optimality, are two crucial thinking styles for creative thinking (Guilford, 1967), but, as highlighted by Zhu et al. (2019), these two thinking styles may not significantly correlate with each other. Motivation, categorized as intrinsic and extrinsic, shows varied effects on creativity, with intrinsic motivation often deemed beneficial, while the impact of extrinsic motivation remains complex (Taylor & Kaufman, 2021). Further research is therefore needed to clarify the relationships among the components of scientific creativity.

Examining the complicated relationships of scientific creativity with these various factors is crucial for China, considering its excellent performance in international science assessments (OECD, 2014, 2019, 2023b), but relatively unimpressive performance in creativity assessments (W. Hu et al., 2004; Park et al., 2021; Wong & Niu, 2013). The Chinese education system, which is notably "exam-centric," prioritizes standard answers in examinations, thereby discouraging students from offering novel and unconventional ideas in classroom settings or examinations (Cheng, 2004). This might explain the difference between science assessments and creativity assessments. Secondary school students in China, who face the National College Entrance Examination, are likely to be the most affected by this exam-centric education system (C. Tan, 2016). In this context, the internal relationships of the components among scientific creativity may be unpredictable and therefore deserve further investigation.

This paper is organized as follows: It begins with a review of the literature on scientific creativity, focusing on assessment instruments, scoring processes, demographic differences in scientific creativity, and the relationships among its components, aiming to identify key research gaps. Next, the rationale for the current study is explained, along with its research questions and hypotheses. The methods section describes the modified C-SCA instrument and outlines a detailed description of the assessment and scoring processes. The following results section reports on the reliability and validity of the instrument, demographic differences in scientific creativity, and the relationships among its components. The discussion section interprets these findings, highlighting the study's limitations and offering directions for future research, and the paper ends with a conclusions section.

Literature review

Scientific creativity

The concept of creativity has been widely discussed in the literature and is generally defined by two key characteristics: novelty and appropriateness (Kaufman & Sternberg, 2019). Novelty is associated with originality or uniqueness, and appropriateness refers to usefulness or effectiveness (Runco & Jaeger, 2012). Glăveanu and Kaufman (2019) differentiate between artistic and scientific creativity, noting that artistic creativity emphasizes novelty, often characterized by divergence, self-expression, and unpredictability, while scientific creativity prioritizes appropriateness, which involves convergence, effective problem-solving, and producing useful outcomes. Therefore, creative ideas in science must be firmly rooted in scientific knowledge and skills to ensure their appropriateness (W. Hu & Adey, 2002), and these ideas should be rigorously validated through logical reasoning and empirical testing to transform them into scientific knowledge (Kind & Kind, 2007).

The multidimensional nature of scientific creativity is well-recognized among researchers in the field (Pont-Niclòs et al., 2024). Various theoretical models, such as the "Scientific Structure Creativity Model (SSCM)" (W. Hu & Adey, 2002), the multi-faceted battery for scientific creativity measurement (Agnoli et al., 2016), and the recent C-SCA model (Xu et al., 2024), illustrate its complexity. Besides scientific knowledge, recognized as a foundational dimension of scientific creativity (Ayas & Sak, 2014; W. Hu & Adey, 2002), divergent and convergent thinking are also essential, with the former enabling individuals to explore a thought space in multiple and diverse directions and the latter requiring them to apply scientific knowledge and logical reasoning to arrive at a preferred solution (de Vries & Lubart, 2019; Xu et al., 2024). Motivation constitutes another critical dimension of scientific creativity, with intrinsic motivation – driven by factors such as enjoyment, interest, or personal challenge – typically enhancing creativity, while extrinsic motivation, arising from rewards, recognition, or external expectations, exerts a more complex influence on the creative process (Taylor & Kaufman, 2021). As a result, the mechanisms involving scientific knowledge, divergent and convergent thinking, as well as intrinsic and extrinsic motivation, warrant further empirical investigation using appropriate assessment instruments.

Scientific creativity assessment instruments

To measure scientific creativity, Lubart et al. (2022) reviewed a number of existing instruments, identifying three main types: accomplishment-based measures, science-based competitions, and psychometric tests. Accomplishment-based measures are based on individuals' creative products, such as science papers; science-based competitions include events like the "Science Olympiad;" psychometric tests require individuals to produce creative and scientific ideas for given problems, and it is this approach that we now discuss.

Most assessment instruments target the measurement of divergent thinking, a key component of scientific creativity (Aschauer et al., 2022; W. Hu & Adey, 2002; Sak & Ayas, 2013). For example, the SCT includes seven open-ended questions for students aged 12 to 18 (W. Hu & Adey, 2002), while the C-SAT consists of five questions for students aged 11 to 14 (Sak & Ayas, 2013). Both instruments include questions related to scientific research. For example, the SCT features an item asking: "If you can take a spaceship to travel in the outer space and go to a planet, what scientific questions do you want to research? Please list as many as you can" (W. Hu & Adey, 2002, p. 394). Similarly, the C-SAT presents an experiment about flies, "requiring students to generate as many hypotheses as they can think of that the researcher might test" (Sak & Ayas, 2013, p. 320). Comparing these two instruments, Huang and Wang (2019) found that the SCT was a better indicator of students' scientific creativity than the C-SAT, as the latter relied more on scientific knowledge. Aschauer et al. (2022) highlighted the need for scientific creativity to be applied to both science and experimental tasks, leading to the development of the "Divergent problem-solving ability in science" (DPAS) test for students aged 10–19. More recently, R. Beaty et al. (2024) developed the "Scientific Creative Thinking Test' (SCTT), whose tasks include generating hypotheses, formulating research questions, and designing experiments, targeting undergraduate students. These four instruments, SCT, C-SAT, DPAS, and SCTT use divergent thinking as an indicator of scientific creativity, but overlook convergent thinking. Convergent thinking is essential for refining and validating the ideas generated through the divergent process, enabling individuals to transform these novel ideas into trusted and correct answers (Cropley, 2006). Zhu et al. (2019) further highlighted that scientific creativity requires not only the generation of diverse ideas, views, or solutions but also the integration and evaluation of these ideas to identify the most fitting answers. Thus, a comprehensive approach to scientific creativity should account for both divergent and convergent thinking (Cropley, 2006; Zhu et al., 2019).

Addressing this, Yang et al. (2019) modified the SCT to include both divergent and convergent thinking tasks. Similarly, de Vries and Lubart (2019) developed the "Evaluation of Potential Creativity" (EPoC) test to assess both divergent-exploratory thinking and convergent-integrative thinking. However, these instruments do not integrate the two thinking styles within the same task. To overcome this, Rusnayati et al. (2019) developed the "Scientific Creative and Critical Thinking Test" (SCCT-Test), which consists of two scientific creative thinking tasks and three scientific critical thinking tasks, with these tasks all related to hydrostatic pressure. These instruments underscore the importance of testing appropriate thinking styles and designing relevant tasks for scientific creativity assessment.

Since scientific creativity is a multidimensional construct, it may not be adequately measured through a single dimension (Agnoli et al., 2016; Xu et al., 2024). Agnoli et al. (2016) developed a multi-faceted test battery incorporating indicators such as creative thinking process, creative achievement, intelligence, and personality, measured using various existing instruments. Agnoli et al. (2016) employed the "Work Preference Inventory" (WPI) (Amabile et al., 1994) to assess students' motivation, though the WPI might not be directly relevant to measuring motivation specific to scientific creativity. To address this limitation, Taylor and Kaufman (2021) introduced the "Creativity Trait Motivation" (CTM) instrument to measure university students' motivation to apply creativity in science learning. Xu et al. (2024) further developed the "Comprehensive Scientific Creativity Assessment" (C-SCA) instrument, incorporating the CTM and measuring students' scientific knowledge, divergent thinking, and convergent thinking through related scientific tasks, but the C-SCA still requires further modifications and empirical validation to establish its robustness and applicability. Therefore, more research is necessary to explore comprehensive assessment methods for scientific creativity, ensuring a holistic understanding of this complex construct.

Scientific creativity scoring

Scoring divergent thinking in scientific creativity assessments poses significant challenges (Reiter-Palmon et al., 2019; Rietzschel et al., 2024; Silvia et al., 2008). Common dimensions in scientific creativity assessment instruments include fluency, flexibility, and novelty (W. Hu & Adey, 2002; Sak & Ayas, 2013). Specifically, fluency scores depend on the number of adequate responses, whereas flexibility and novelty scores concern the diversity and originality of those responses (W. Hu & Adey, 2002). However, not all assessment instruments incorporate these three dimensions in their scoring criteria. For instance, the DPAS instrument evaluates only fluency and flexibility (Aschauer et al., 2022), and the divergent thinking tasks in the EPoC instrument are assessed based only on fluency and novelty (de Vries & Lubart, 2019), and the tasks in the SCTT are scored exclusively on novelty (R. Beaty et al., 2024).

The rarity of flexibility and novelty scores is due to the fact that the former requires a complex categorization process, while the latter can be influenced by the sample size (Reiter-Palmon et al., 2019). Flexibility is scored using preexisting categories constructed on given data; nevertheless, broad categories may yield few total categories, and narrow categories may result in too many categories, which influences the flexibility score (Reiter-Palmon et al., 2019). Novelty scores may vary with sample size, as common responses may appear less frequently in smaller samples, artificially inflating their novelty (Forthmann et al., 2017). As a result, the potentially subjective categorization process and the sample size can affect the final results (R. E. Beaty & Johnson, 2021; Xu et al., 2024).

Labor costs present another challenge, as raters must code thousands of responses, making creativity research cumbersome (R. E. Beaty & Johnson, 2021; Rietzschel et al., 2024). R. E. Beaty and Johnson (2021) addressed this with an automated creativity assessment tool, "SemDis," which uses natural language processing to quantify the semantic relatedness of texts. According to the associative theory of creativity, high-creative individuals exhibit flexible semantic networks, connecting remote concepts, which SemDis quantifies to measure creativity (R. E. Beaty & Johnson, 2021). However, SemDis requires manual spell-checking and is therefore more suitable for simple texts (R. E. Beaty & Johnson, 2021). In the context of scientific creativity assessment, participants' responses can be more complex, and raters are also required to evaluate the correctness (or appropriateness) of these responses (Xu et al., 2024). This complexity can limit the effectiveness of automated scoring methods like SemDis for scientific creativity tasks. Rietzschel et al. (2024) proposed using an idea pool as a convenient solution. In this method, researchers create a predefined pool of ideas that have been previously evaluated for their creativity levels, so that participants' responses are then compared against this pool to determine their creativity. Similarly, Xu et al. (2024) suggested that future users of the C-SCA could assign a corresponding score to each response through extensive sampling and a series of processing steps. Considering these scoring challenges – such as the subjective categorization process, the influence of sample size on novelty scores, and the labor-intensive nature of scoring – further research is needed to address these issues, and some automated creativity assessment tools, combined with an idea pool or predetermined criteria, may be helpful in eliminating the need for repetitive assessments of flexibility and novelty.

Demographic differences in scientific creativity

Considering the multidimensional nature of scientific creativity, previous studies have primarily focused on the influence of demographic variables such as gender and family background, exploring various dimensions including scientific knowledge (Morgan et al., 2016; Voyer & Voyer, 2014), motivation (Potvin & Hasni, 2014; Steinmayr et al., 2012), and divergent thinking (Castillo-Vergara et al., 2018; Pont-Niclòs et al., 2024). In the context of science examinations, which typically assess students' scientific knowledge, Voyer and Voyer (2014) conducted a meta-analysis of 369 studies published in English on gender differences in scholastic achievement across levels from elementary school to university, finding that female students outperformed males in science subjects. However, Shao and Pang (2016) reviewed studies on gender differences in China's College Entrance Examination and found that the female advantage was limited to language subjects, with some studies showing that males performed better than females in science examinations. In terms of motivation, Potvin and Hasni (2014) systematic review of students' interest and motivation for science study revealed a clear preference for physics among boys, while both genders showed similar preferences for chemistry; however, girls were more inclined toward biology at the K-12 levels. Additionally, self-reports on creativity levels indicated that males tended to express greater confidence in their science-related creativity compared to females (Baer & Kaufman, 2008). Regarding divergent thinking, a key component of creativity assessments, Nakano et al. (2021) reviewed 133 publications from 1975 to 2020, finding that 45% reported gender differences favoring women, while 23% favored men. Specifically, in assessments targeting scientific creativity, Pont-Niclòs et al. (2024) analyzed the performance of 780 Spanish upper secondary school students ($N_{male} = 404$, $N_{female} = 376$); girls scored statistically significantly better than boys. However, W. Hu et al. (2004) found cross-cultural differences, with English female adolescents outperforming males in scientific creativity, while Chinese males outperformed females. This male advantage, however, was not observed in Xu et al. (2024) study in China.

Another relevant factor is family background, which has been widely discussed as affecting students' science achievement (J. Liu et al., 2020; Morgan et al., 2016). In the context of China's one-child policy, Y. Liu and Jiang (2021) found mixed findings, highlighting that while some studies suggested that only children were more likely to develop dependence, self-centeredness, indifference, or poor interpersonal skills due to their being spoiled in the family and lack of sibling interactions, other studies have provided empirical evidence showing that only children tend to manifest higher cognitive abilities and achieve higher academic performance (e.g., Wei et al., 2016), though limited research has focused on their creativity performance. Additionally, Morgan et al. (2016) noted that children from lower socioeconomic status (SES) families, determined by parents' educational levels, occupations, and family income, have fewer early opportunities to learn about science due to their parents' lower educational levels and possessing less scientific knowledge. J. Liu et al. (2020) supported this with a meta-analysis involving 78 independent samples of Chinese students, showing that those with higher SES had better scientific attainment, possibly due to access to higher-quality educational resources. In addition, children with more educated parents tend to be more confident in learning science and exhibit greater motivation, as their parents are more likely to value science education and provide adequate science learning resources (Steinmayr et al., 2012). Based on "the development theories of creativity," family background plays an important role in nurturing individuals' creative potential (Kaufman & Sternberg, 2019, p. 26). However, few empirical studies have examined the relationship between family background and creativity (Dai et al., 2012). Two studies illustrate the relationship at school level, concluding that schools with higher SES, evaluated by school size, number of teachers, free lunch eligibility, or parental education levels, provide better learning resources, fostering more creative students (Castillo-Vergara et al., 2018; Dai et al., 2012). Reviewing previous studies on scientific creativity assessments, such as SCT (W. Hu & Adey, 2002), C-SAT (Sak & Ayas, 2013), and C-SCA (Xu et al., 2024), none of them have analyzed the impact of family backgrounds on students' scientific creativity levels. As a result, when discussing demographic differences in scientific creativity, researchers should first account for its multidimensional nature and specify the dimensions under investigation. Gender differences need to be examined with consideration of specific subjects and diverse contexts, while the influence of family background factors, such as being an only child, parental occupations and education, or family income, requires further empirical evidence to clarify their role in shaping children's scientific creativity.

Relationships among the components of scientific creativity

Previous studies have also empirically investigated the multidimensional structure of scientific creativity (Xu et al., 2024). Many studies agree that divergent thinking and convergent thinking are positively related in scientific creativity assessment (de Vries & Lubart, 2019; Yang et al., 2019), with convergent thinking acting as a threshold necessary for effectively integrating numerous novel ideas into creative products (Zhu et al., 2019). However, there are inconsistent findings regarding the influence of scientific knowledge. For instance, Yang et al. (2019) found that scientific knowledge had a significantly positive effect on divergent thinking, though this effect did not extend to convergent thinking, a pattern not consistently observed in other studies (Conradty & Bogner, 2019; Xu et al., 2024).

Regarding motivation, the literature has consistently shown that intrinsic motivation is conducive to divergent thinking in both western and eastern populations (Amabile, 1983; Du et al., 2019; Wang et al., 2021). When individuals are driven by personal interest in a task, they tend to explore creative ways to complete it rather than relying only on traditional methods (Wang et al., 2021). Studies of the relationship between extrinsic motivation and divergent thinking, however, have yielded contradictory results. Some studies have reported that extrinsic motivation can promote individuals' divergent thinking (Agnoli et al., 2018; Eisenberger & Rhoades, 2001), while others have suggested a negative relationship (Cooper & Jayatilaka, 2006; Xue et al., 2020). Cooper and Jayatilaka (2006) argued that extrinsic motivation might reduce individuals' freedom, confining their actions to well-known behaviors aimed at obtaining rewards. The motivations discussed earlier were primarily task-oriented, whereas Xu et al. (2024) study focused on motivations related to scientific creativity, exemplified by extrinsic motivation, where students are externally expected to demonstrate scientific creativity and adjust their behaviors accordingly. Drawing on Amabile's (2018) motivational synergy theory, synergistic extrinsic motivators, which can "support one's sense of competence or enable one's deeper involvement with the task itself" (p.118), can positively interact with intrinsic motivation to enhance creativity. In science classrooms, external expectations and rewards for students' creative behavior may serve as synergistic extrinsic motivators, stimulating the creative process. However, this hypothesis requires further empirical validation. As a result, while existing research has investigated key components – such as divergent and convergent thinking, scientific knowledge, and motivation – that influence scientific creativity, the complex interplay among these components remains underexplored, especially in the context of students' scientific creativity in science classrooms.

Current study

This study aims to address key research gaps by providing a comprehensive assessment of scientific creativity with an objective scoring process, examining demographic differences, and exploring the complex relationships among its components. Accordingly, it investigates the following research questions and proposes corresponding hypotheses:

Research question 1: Is the modified C-SCA a valid instrument for measuring students' scientific creativity?

Associated hypothesis: The modified C-SCA is a valid instrument for measuring students' scientific creativity.

Research question 2: What are the demographic differences in students' scientific creativity, including their scientific knowledge, motivation for scientific creativity, as well as divergent and convergent thinking?

Associated hypotheses: Male students outperform female students in the scientific creativity assessment. Only children perform better than children with siblings. Students from families where parents have higher educational levels, hold better occupations, or possess higher family incomes achieve higher scores in the scientific creativity assessment.

Research question 3: What are the relationships among the components of scientific creativity, including scientific knowledge, and motivation in scientific creativity (intrinsic and extrinsic motivation), as well as thinking styles (divergent and convergent thinking)?

Associated hypotheses: Divergent and convergent thinking exhibit a mutually supportive relationship. Scientific knowledge, along with both types of motivation, positively influences both types of thinking styles.

Methods

Participants

All 522 10th-grade students from a secondary school in Taiyuan City, Shanxi Province, China, were invited to participate in two assessments by completing papers. A power analysis was conducted before the choice of the sample. Details can be found in Appendix 1 of the Supplementary Material. The first assessment was conducted on October 26, 2023, and the second on January 8, 2024. Thus, students were assessed on two separate occasions, approximately ten weeks apart. For clarity, we referred to these as the first assessment and the second assessment. A total of 441 students took part in the first assessment, and 409 students participated in the second assessment, as some students chose not to participate. For the purposes of data cleaning, papers where participants did not complete all divergent thinking tasks were considered ineligible and thus excluded. This criterion was implemented because each divergent thinking task served as a prerequisite for subsequent tasks; participants needed to ask scientific questions and propose solutions before elaborating on and evaluating them. Consequently, 49 papers from the first assessment and 17 papers from the second assessment were disqualified. After matching the participants from the two assessments, a total of 347 participants remained eligible for further analysis, with a nearly even gender distribution (49.6% male, 50.4% female). This resulted in a qualification rate of 78.7%.

Assessment procedure

The assessments were undertaken in normal school hours as a part of regular teaching. Before the first assessment, the principal and teachers reviewed the information sheet and signed the informed consent forms. Next, students received an information sheet explaining that the purpose of the research was to assess scientific creativity, that participation was voluntary, and that they could withdraw at any time without needing to provide an explanation. By signing their names and submitting their completed assessments, students indicated their informed and voluntary participation. This process is evident in the participation numbers, with 441 students participating in the first assessment and 409 in the second, as some students opted not to submit their assessments. The classroom teachers in each class were responsible for the two assessments, and they had been trained in each assessment by the first author before the assessment was undertaken. A total of 70 minutes was allocated to the students participating in the first assessment, while 65 minutes was allocated in the second assessment. The difference in time allocation was because the first assessment contained eight additional personal information questions.

Instrument

This study used a modified version of the C-SCA instrument to evaluate the scientific creativity of participating students. The original C-SCA was validated in a pilot study (Xu et al., 2024), and the pilot version of the instrument required some modification. The revised C-SCA (Version A and Version B) can be found in Appendix 2 of the Supplementary Material. The C-SCA has three dimensions: scientific knowledge, students' motivation in scientific creativity, and thinking styles.

Students' scientific knowledge was assessed through their performance on physics, chemistry, and biology tests administered by the school on October 13, 2023, and December 20, 2023. These tests were not specifically designed for this study, but covered science content previously taught to students. The two scientific knowledge examinations were administered to the same students, with each student completing the same set of papers in each examination. The total scores of the three subjects in each of the two examinations were used to determine the students' performance in science knowledge in the first assessment and second assessment, respectively.

Students' motivation in scientific creativity was assessed using the Chinese version of the Creative Trait Motivation (CTM) scale, originally developed by Taylor and Kaufman (2021). The Chinese version of the CTM scale demonstrates satisfactory reliability and validity (Xu et al., 2024). This original scale comprises 20 items and evaluates three dimensions: intrinsic motivation, extrinsic motivation, and amotivation. In this study, the CTM only includes intrinsic motivation (ten items) and extrinsic motivation (six items), excluding amotivation (four items), with both specifically reflecting students' motivation in the context of scientific creativity. Responses were collected using a 5-point Likert scale, and participants were required to complete their self-reports during the assessments.

Students' divergent thinking and convergent thinking styles were measured by the "Scientific Creativity Test for Upper Secondary School Students" (SCT-USSS) (Xu et al., 2024). SCT-USSS consists of three tasks, each with four questions, and comes in two versions (to allow the test to be used when, for instance, evaluating the effects of an intervention on students' scientific creativity, with one version being used before the intervention, and the other version after the intervention). Versions A and B vary in the content of the tasks. Compared with the SCT-USSS used in Xu et al. (2024) study, the modified versions used in this study featured two adjustments: First, the presentation of Q5 was changed. The

Table 1. Scientific creativity test for upper secondary school students (SCT-USSS).

Subject	Task	Question type	Thinking style
Biology	Biodiversity and environment	Q1: Ask science questions	Divergent thinking
	A: Chinese sturgeon	Q2: Propose solutions	
	B: South China tiger	Q3: Conduct experiment	Convergent thinking
		Q4: Evaluate solutions	
Chemistry	Chemistry and sustainable development	Q5: Unusual uses	Divergent thinking
	A: Plastic bottles	Q6: Propose solutions	
	B: Plastic bags	Q7: Conduct experiment	Convergent thinking
		Q8: Evaluate solutions	
Physics	Sound and light	Q9: Imagination	Divergent thinking
	A: Roadway noise	Q10: Propose solutions	
	B: Light pollution	Q11: Conduct experiment	Convergent thinking
		Q12: Evaluate solutions	

Note. Q1-Q12 indicates the order in which each question appears in the test. A and B refer respectively to Version A and Version B. Modifications were made based on Xu et al. (2024, p. 10).

original version, “Please write down as many scientific uses for plastic bottles (plastic bags) as possible,” was modified to “Please write down as many uses for plastic bottles (plastic bags) as possible. Do not be limited by their size. You may use as many of them as you like.” Secondly, the sequence of convergent thinking questions in the three tasks was rearranged, with the conducting experiment placed first, followed by evaluating solutions. The structural design of the SCT-USSS can be found in Table 1.

Scoring process

Students’ scores on physics, chemistry, and biology tests were directly obtained from the school. Students’ motivation in scientific creativity was the sum of intrinsic motivation and extrinsic motivation. The scoring procedure for the SCT-USSS involved two components: scoring for divergent thinking, and scoring for convergent thinking. The latter was a relatively straightforward process, with two raters independently conducting scoring according to established criteria (Xu et al., 2024). The former, however, presented a challenge, as elaborated below. Table 2 shows the scoring criteria for the SCT-USSS.

The scoring for divergent thinking was based on three aspects: fluency, flexibility, and novelty, assessed through the first and second questions of each task. Fluency was determined by the number of scientific questions or solutions provided. Scoring flexibility required all responses to be categorized. Categorization allowed evaluation of a student’s ability to think about a question from various perspectives. Scoring novelty required calculation of the frequency of students’ responses. Because of the similarity of some responses, a second categorization was undertaken to yield sub-categories, which could be used to count the frequency of students’ responses. Following the development of the sub-category list, each student’s response was assigned to one of the identified sub-categories. The probability of each sub-category was calculated by dividing the frequency of responses within that sub-category by the total number of responses for the entire question. For example, if a specific sub-category contained 40 responses out of 1,200 total responses, its proportion was about 3.3%, and the sub-category was awarded 2 points. Each student’s final novelty score was

Table 2. The scoring criteria for the SCT-USSS.

	Dimension	Scoring criteria
Divergent thinking	Fluency	Score of 1 point for each response.
	Flexibility	Score of 1 point for each category of response.
	Novelty	Score is 2 points if probability of each sub-category is less than 5%, 1 point if between 5% and 10%, and 0 points if greater than 10%; the final score is the sum of all sub-categories.
Convergent thinking	Critique	1 point: only gives advantages of this solution, without disadvantages. 2 points: gives both advantages and disadvantages of this solution, but without explanations. 3 points: gives both advantages and disadvantages of this solution, and also explains the reasons for not choosing other solutions.
	Elaboration	1 point: very brief or no elaboration. 2 points: detailed elaboration. 3 points: provides both text and illustrations to further explain the process and details of the experiment and solution.
	Logicality	1 point: the whole solution and experiment has many scientific and logical errors. 2 points: only a few parts of the solution and experiment are not scientific and logical, and the majority of them are reasonable. 3 points: the solution and the experiment are very scientific and logical, and they exist in reality and have a realistic basis.

Note. The scoring criteria are taken from Xu et al. (2024, p. 11).

obtained by summing the novelty points assigned to all their responses. Thus, the categorization process for categories and sub-categories was pivotal in determining both flexibility and novelty scores. In the practical scoring process, the detailed or broad categorization would impact the reliability and validity of the instrument, and the final outcomes of participants (Xu et al., 2024); however, some scientific creativity assessment studies fail to explain the categorization process (Ayas & Sak, 2014; W. Hu & Adey, 2002). To address these issues, this study conducted two rounds of categorization and provided a detailed description of how the final categorization list was determined.

The first round of categorization involved two researchers. One researcher reviewed all responses to produce a comprehensive categorization. Additionally, to facilitate a meaningful comparison between Versions A and B, an identical number of categories was maintained across corresponding tasks. For example, if biology task 1 in Version A included eight categories and 30 sub-categories, the Version B responses for the same task were categorized into eight categories and 30 sub-categories. Subsequently, the revised categorization underwent review by another researcher to ensure the validity of the categories.

The second round of categorization aimed to employ pre-calculation to assess the acceptability of the categorization. The process involved randomly selecting 50 of the 347 participants. This sample was then used to evaluate whether the categorization resulted in acceptable reliability and validity for the SCT-USSS. The initial results indicated that Q10 could not effectively assess students' divergent thinking after the first categorization. Thus, in the second round of categorization, we increased the number of categories of Q10 and then used these to recalculate the same participants' responses. The final results showed that the second round of categorization ensures acceptable reliability and validity of SCT-USSS. Therefore, the results of the second round of categorization were used to calculate students' flexibility and novelty scores. An example of the categorization lists for the Q5 can be found in Appendix 3 of the Supplementary Material.

Statistical analyses

Reliability and validity of the C-SCA

The reliability and validity of the CTM and SCT-USSS were assessed using Mplus 8. For reliability, internal consistency was assessed for both the CTM and SCT-USSS, with a Cronbach's alpha value greater than 0.7 considered acceptable (Taber, 2018). Additionally, inter-scorer correlations for the convergent thinking questions were calculated to ensure the reliability of the scoring system. For the determination of validity, previous studies have described the theoretical frameworks and task relevance, with the instruments being reviewed by experts or teachers (Taylor & Kaufman, 2021; Xu et al., 2024). This study focused on construct validity, with Confirmatory Factor Analysis (CFA) conducted to evaluate the hypothesized models. Maximum likelihood estimation was chosen, as it aligns with the multivariate normality assumption and facilitates robust model testing with our dataset.

For the CTM, a two-factor model was specified, with intrinsic motivation measured by ten indicators and extrinsic motivation measured by six indicators.

For the SCT-USSS, the distinct constructs and scoring criteria necessitated two separate single-factor models for divergent and convergent thinking. The divergent thinking model included six indicators (Q1, Q2, Q5, Q6, Q9, and Q10), each representing the total score of fluency, flexibility, and novelty for the respective question. The convergent thinking model comprised three indicators derived by combining specific question pairs: Indicator 1 (Q3 + Q4), Indicator 2 (Q7 + Q8), and Indicator 3 (Q11 + Q12). These indicators incorporated elaboration and logicality scores from Q3, Q7, and Q11, as well as critique scores from Q4, Q8, and Q12.

For the convergent thinking model, which comprised only three indicators, traditional fit indices were not computed due to the model's simplicity and the limited number of parameters involved. As Brown (2015) noted, models with such a minimal structure are often evaluated based on the interpretability and strength of factor loadings, rather than conventional fit indices.

For the CTM and divergent thinking models, model fit was assessed using fixed cutoff values commonly applied in creativity assessment research (Ayas & Sak, 2014; Plucker, 1999; Taylor & Kaufman, 2021). Following the criteria established by L. Hu and Bentler (1999), good model fit was indicated by values of SRMR $\leq$ .08, RMSEA $\leq$ .06, and CFI and TLI $\geq$ .95. The cutoff used for factor loading was .30 (Brown, 2015).

Demographic statistics of the C-SCA

To examine potential demographic differences in students' C-SCA performance, data from the first assessment were analyzed using SPSS 29. Independent-samples t-tests were performed to compare differences between binary groups (e.g., gender). One-way ANOVA was employed to assess differences across multi-level demographic variables (e.g., mother's educational level).

Relationships among the components of the C-SCA

To explore relationships among the components of the C-SCA – scientific knowledge, motivation in scientific creativity (comprising intrinsic motivation and extrinsic motivation), and thinking styles (comprising divergent thinking and convergent thinking) – Pearson correlation analyses were conducted using SPSS 29. Hierarchical regression analyses were then performed to examine the effects of these variables on both divergent and convergent thinking, controlling for relevant demographic factors.

Results

Reliability and validity of the C-SCA

Creative trait motivation (CTM) scale

Table 3 shows that the CTM was used in the two assessments with satisfactory internal consistency, with Cronbach's α ranging from 0.83 to 0.92 (first assessment: α = 0.84; second assessment: α = 0.88). In terms of validity, analyses of residuals and modification indices (MI) identified high MI values among several indicators in both assessments. Modifications were applied based on the MI > 3.84 threshold (Brown, 2015) and were limited to indicators within the same factor to ensure theoretical coherence, while aligning with the original CTM structure to maintain framework consistency. These adjustments led to an improved model fit, as detailed in Table 4.

Table 3. Internal consistency measures for CTM.

	Scale	Cronbach's α	
The first assessment	Intrinsic motivation	0.88	0.84
	Extrinsic motivation	0.83	
The second assessment	Intrinsic motivation	0.92	0.88
	Extrinsic motivation	0.86	

Scientific creativity test for upper secondary school students (SCT-USSS)

In terms of SCT-USSS, the two assessments each contained 12 questions, with similar question types but different content, with the second assessment showing acceptable internal consistency (α = 0.74) while the first assessment showed modest internal consistency (α = 0.64). Internal consistency analysis was also performed for both divergent and convergent thinking, yielding Cronbach's α values ranging from 0.61 to 0.78. Further details are presented in Table 5.

Internal consistency analysis was also conducted for each question in the two assessments of the SCT-USSS. Table 6 shows that after removing specific questions, the Cronbach's α coefficient for the remaining five questions decreased compared to the original six questions. Furthermore, Pearson's correlation coefficients revealed significant correlations between each question and the respective corrected style scores. Therefore, all questions exhibited robust internal consistency.

To ensure the reliability of the scoring system for convergent thinking (Q3, Q4, Q7, Q8, Q11, Q12), an assessment of interpretability was conducted involving independent scorers. The scorers comprised an individual unaffiliated with the research project and the first author. Scoring for the 347 participants was independently conducted by both scorers, and the Pearson product-moment correlation coefficients between their assessments are given in Table 7. Correlation coefficients ranged from 0.73 to 0.92, with overall correlations for convergent thinking questions being 0.88 for the two

Table 4. Model fit measures for CTM.

	Chi-square (X^2)	Degrees of freedom (df)	SRMR	RMSEA	CFI	TLI
The first assessment	170.204	88	0.061	0.052	0.957	0.942
The second assessment	137.160	86	0.048	0.041	0.984	0.978

Table 5. Internal consistency measures for SCT-USSS.

	Thinking style	Indicator	Cronbach's α		
The first assessment	Divergent thinking	Fluency	0.72	0.67	0.64
		Flexibility	0.51		
		Novelty	0.60		
	Convergent thinking	Elaboration	0.49	0.61	
		Logicality	0.47		
		Critique	0.63		
The second assessment	Divergent thinking	Fluency	0.81	0.78	0.74
		Flexibility	0.62		
		Novelty	0.72		
	Convergent thinking	Elaboration	0.74	0.73	
		Logicality	0.74		
		Critique	0.72		

Table 6. Internal consistency and correlation analysis of SCT-USSS questions.

	Thinking style	Questions	Cronbach's α if specific question removed	Pearson's r with corrected divergent/convergent thinking scores
The first assessment	Divergent thinking	Q1	0.62	0.46***
		Q2	0.60	0.52***
		Q5	0.64	0.37***
		Q6	0.64	0.37***
		Q9	0.63	0.40***
		Q10	0.64	0.36***
	Convergent thinking	Q3	0.57	0.34***
		Q4	0.58	0.36***
		Q7	0.54	0.40***
		Q8	0.56	0.44***
		Q11	0.59	0.33***
		Q12	0.56	0.41***
The second assessment	Divergent thinking	Q1	0.72	0.60***
		Q2	0.74	0.60***
		Q5	0.74	0.53***
		Q6	0.75	0.51***
		Q9	0.75	0.53***
		Q10	0.76	0.48***
	Convergent thinking	Q3	0.68	0.51***
		Q4	0.71	0.46***
		Q7	0.66	0.57***
		Q8	0.71	0.46***
		Q11	0.66	0.59***
		Q12	0.72	0.36***

Note. *$p < .05$, **$p < .01$, ***$p < .001$.

Table 7. Inter-scorer correlations for the convergent thinking questions.

	Q3	Q4	Q7	Q8	Q11	Q12	All
The first assessment	0.80***	0.88***	0.77***	0.89***	0.84***	0.92***	0.88***
The second assessment	0.73***	0.91***	0.78***	0.87***	0.80***	0.91***	0.88***

Note. *$p < .05$, **$p < .01$, ***$p < .001$.

assessments. These findings suggest satisfactory agreement in the scoring process.

Regarding the validity of the SCT-USSS, for the divergent thinking model, analyses of residuals and MI using data from the first assessment revealed high MI values between Q1 and Q2 (MI = 17.40) and between Q9 and Q10 (MI = 17.01). These elevated MI values, combined with the fact that these item pairs addressed the same task, provided theoretical and empirical justification to correlate the error terms of Q1 and Q2, as well as those of Q9 and Q10. After these modifications, the model exhibited good fit indices ($X^2 = 11.71$, df = 7, SRMR = 0.024, RMSEA = 0.044, CFI = 0.984, TLI = 0.965). Using data from the second assessment, the divergent thinking model was tested without any modifications and still showed good fit indices ($X^2 = 27.74$, df = 9, SRMR = 0.034, RMSEA = 0.077, CFI = 0.963, TLI = 0.939).

Table 8. Factor analysis results for the divergent thinking questions.

	Factor loadings of each question	
Question	The first assessment	The second assessment
Q1	0.52	0.71
Q2	0.60	0.71
Q5	0.49	0.62
Q6	0.52	0.57
Q9	0.45	0.60
Q10	0.39	0.54

Table 9. Factor analysis results for the convergent thinking.

		Factor loadings of each question	
Task	Question	The first assessment	The second assessment
Biology	Q3 Q4	0.51	0.67
Chemistry	Q7 Q8	0.74	0.83
Physics	Q11 Q12	0.37	0.62

Table 8 presents the standardized factor loadings for each divergent thinking question from the two assessments. Notably, the factor loadings for all items increased in the second assessment compared to the first, and Q10 consistently exhibited the smallest factor loadings across both assessments (0.39 and 0.54, respectively).

For the convergent thinking model, Table 9 shows the standardized factor loadings of each convergent thinking task for each assessment. Similarly, factor loadings in the second assessment were higher across all tasks compared to the first assessment, and the physics task consistently exhibited the smallest factor loadings across both assessments (0.37 and 0.62, separately).

Demographic statistics of the C-SCA

The summary of participants' scientific knowledge performance is presented in Appendix 4 of the Supplementary Material. A significant difference in scientific knowledge was found between genders (t = 3.10, p = .002), with males (240.22) scoring higher than females (230.87). Specifically, males scored significantly higher than females in physics (t = 3.44, p < .001) and chemistry (t = 3.15, p = .002), with scores of 70.32 and 87.41 for males and 65.60 and 83.84 for females, respectively. Additionally, a significant difference in scientific knowledge was observed between participants who were only children (238.55) and those who had siblings (231.60) (t = 2.28, p = .023), with the former's physics scores (69.52) significantly exceeding the latter's (65.91) (t = 2.59, p = .10). Regarding family background, significant differences were found in scientific knowledge based on mother's educational level (F = 1.99, p = .040) and mother's occupation (F = 2.01, p = .020), while no significant differences were observed based on father's educational level (F = 1.76, p = .083) or father's occupation (F = 1.72, p = .056)

Participants from very affluent families (50.00) and affluent families (40.75) demonstrated significantly higher intrinsic motivation for scientific creativity compared to participants from average families (38.01) and least affluent families (37.31) (F = 3.41, p = .018) (see Appendix 5 of the Supplementary Material). There were no significant differences observed in the scores of divergent thinking and convergent thinking across demographic variations (see Appendix 6 of the Supplementary Material).

Relationships among the components of the C-SCA

Table 10 shows that divergent thinking significantly and positively correlated with scientific knowledge (r = 0.18, p < .001) and convergent thinking (r = 0.28, p < .001), but significantly and negatively correlated with extrinsic motivation in scientific creativity (r = –0.15, p = .007). Additionally, convergent thinking significantly and positively correlated with scientific knowledge (r = 0.22, p < .001), while intrinsic motivation significantly and positively correlated with scientific knowledge (r = 0.11, p=.043) and extrinsic motivation in scientific creativity (r = 0.19, p < .001). Although these correlations were statistically significant, their effect sizes were generally weak.

Table 10. Correlational matrix for measured indicators in the first assessment (N = 347).

	1	2	3	4	5
1 Scientific knowledge	1				
2 Intrinsic motivation	0.11*	1			
3 Extrinsic motivation	−0.05	0.19***	1		
4 Divergent thinking	0.18***	0.03	−0.15**	1	
5 Convergent thinking	0.22***	0.04	0.00	0.28***	1

Note. *p<.05, **p<.01, ***p<.001.

Table 11. Summary of hierarchical regression analysis for variables predicting divergent thinking in the first assessment (N = 347).

Variable	B	SE B	β	R^2	ΔR^2	F for change in R^2
Model 1				0.02	0.02	1.02
Constant	81.42	13.01				
Gender	−2.08	2.67	−0.04			
One-child	3.19	2.75	0.06			
Mother's educational level	0.34	0.68	0.03			
Mother's occupation	−0.57	0.37	−0.09			
Family's economic condition	2.29	3.17	0.04			
Model 2				0.13	0.12	11.22***
Constant	33.24	18.16				
Gender	−1.44	2.56	−0.03			
One-child	4.92	2.62	0.10			
Mother's educational level	0.47	0.64	0.04			
Mother's occupation	−0.43	0.35	−0.07			
Family's economic condition	3.11	3.04	0.05			
Scientific knowledge	0.09	0.05	0.10			
Intrinsic motivation	0.08	0.19	0.02			
Extrinsic motivation	−0.67	0.25	−0.14**			
Convergent thinking	1.84	0.36	0.27***			

Note. *p<.05, **p<.01, ***p<.001.

Table 12. Summary of hierarchical regression analysis for variables predicting convergent thinking in the first assessment (*N* = 347).

Variable	B	SE B	β	R^2	ΔR^2	F for change in R^2
Model 1				0.02	0.02	1.40
Constant	18.95	1.91				
Gender	−0.12	0.39	−0.02			
One-child	−0.74	0.40	−0.10			
Mother's educational level	−0.15	0.10	−0.09			
Mother's occupation	−0.04	0.06	−0.04			
Family's economic condition	−0.50	0.47	−0.06			
Model 2				0.14	0.12	11.28***
Constant	9.38	2.63				
Gender	0.18	0.38	0.02			
One-child	−0.75	0.39	−0.10			
Mother's educational level	−0.16	0.09	−0.10			
Mother's occupation	−0.00	0.05	−0.00			
Family's economic condition	−0.74	0.45	−0.09			
Scientific knowledge	0.02	0.01	0.18***			
Intrinsic motivation	0.01	0.03	0.02			
Extrinsic motivation	0.03	0.04	0.05			
Divergent thinking	0.04	0.01	0.27***			

Note. *p<.05, **p<.01, ***p<.001.

Hierarchical regression analyses were conducted to investigate the effects of additional variables on both divergent and convergent thinking. Control variables were selected based on demographic factors that showed statistically significant impacts on scientific knowledge, intrinsic motivation, extrinsic motivation, divergent thinking, or convergent thinking in prior descriptive statistical analysis. Consequently, the following variables were included as controls in the hierarchical regression model: gender, one-child status, mother's educational level and occupation, as well as family's current economic condition.

For divergent thinking (see Table 11), Model 1, which comprised demographic information, did not yield statistically significant results (p=.303). After adding scientific knowledge, intrinsic motivation, extrinsic motivation, and convergent thinking in Model 2, these variables explained an additional 12% of the variance in divergent thinking, with this change in R^2 being significant (F change (4, 337) = 11.22, $p < .001$). In Model 2, convergent thinking showed a statistically significant positive effect on divergent thinking ($p < .001$), while extrinsic motivation was found to have a statistically significant negative effect on divergent thinking (p=.006).

For convergent thinking (see Table 12), Model 1 did not yield statistically significant results (p=.225). Upon entry of scientific knowledge, intrinsic motivation, extrinsic motivation, and divergent thinking in Model 2, these variables explained an additional 12% of the variance in convergent thinking, with this change in R^2 being significant (F change (4, 337) = 11.28, $p < .001$). In Model 2, both scientific knowledge ($p < .001$) and divergent thinking ($p < .001$) showed statistically significant positive effects on convergent thinking.

Discussion

The purpose of this study was to assess whether the modified C-SCA is a valid instrument for measuring students' scientific creativity. The findings support the modified C-SCA, providing empirical evidence for its reliability and validity with the larger sample size employed in this study. Compared to the original version of the C-SCA (Xu et al., 2024) and other scientific creativity assessment instruments (W. Hu & Adey, 2002; Sak & Ayas, 2013), this study makes a significant contribution by providing clear scoring criteria with objective categorization for evaluating divergent thinking tasks. This addresses previous challenges, such as the subjectivity inherent in categorization (R. E. Beaty & Johnson, 2021) and the influence of sample size on divergent thinking scores (Reiter-Palmon et al., 2019). Additionally, the final categorization results generated by our study can serve as the "idea pool," as recommended by Rietzschel et al. (2024), so that future researchers can use this predefined pool of ideas to score students' responses, greatly reducing their workload.

A key aspect that warrants further discussion is the reliability of the SCT-USSS and the factor loadings of some of its items. Compared to the second assessment, the overall reliability of the first assessment of the SCT-USSS did not meet acceptable standards. This relatively low reliability can be attributed to two main factors. First, the SCT-USSS assesses both divergent and convergent thinking, which are complex constructs with different scoring criteria. As highlighted by Taber (2018), measuring such multifaceted cognitive constructs in science education often results in lower Cronbach's alpha values. A similar pattern was observed in Yang et al. (2019) scientific creativity assessment instrument, which also includes both divergent and convergent thinking constructs, yielding lower-than-expected reliability values. Secondly, the time allocation during the first assessment may have influenced students' ability to maintain consistent effort across all items. Indeed, the factor loadings for Q10 in the divergent thinking tasks and the physics tasks (Q11 + Q12) in the convergent thinking model were consistently the lowest across both assessments, which might reflect this challenge posed by time constraints. In the initial stages, students were encouraged to generate as many responses as possible, which may have resulted in insufficient time for completing later tasks. This phenomenon aligns with previous findings on the time-related challenges inherent in divergent thinking assessments (Reiter-Palmon et al., 2019). As Glover et al. (1989) observed, examinees often struggle to maintain a steady pace throughout a creativity test, which can negatively affect the overall reliability. Notably, an improvement in factor loadings observed during the second assessment for both divergent and convergent thinking tasks suggests that these students may have adapted to the assessment format over time. Familiarity with the test likely enabled them to manage their time more effectively, ensuring a more balanced effort across all tasks. While this adaptation can be seen as a positive development in test-taking skills, it also raises concerns about the potential introduction of construct-irrelevant variability, which could impact the reliability of the assessment. Several strategies can be considered to improve reliability in future iterations of the SCT-USSS. For a start, providing students with clear instructions before the assessment begins, such as encouraging them to review the entire test before they start, would help them better allocate their time. Additionally, reminding students of the time remaining ten minutes before the end of the assessment could further support effective time management. Moreover, future versions of the SCT-USSS could introduce a broader range of themes for the tasks. For example, the current A and B versions in biology both focus on animal protection, so diversifying the task themes could help reduce familiarity bias.

This study also addresses the second research question regarding demographic differences in students' scientific creativity by separately analyzing its various components and examining the influence of multiple demographic variables. In terms of scientific knowledge, the findings support the hypothesis that male students' scientific knowledge scores would be statistically significantly higher than females, aligning with previous research (Shao & Pang, 2016). Similarly, only children scored higher in scientific knowledge than children with siblings, consistent with previous findings (Y. Liu & Jiang, 2021; Wei et al., 2016). In the family environment, parental involvement is the most critical factor influencing academic performance (Wei et al., 2016). Research in China suggests that only children typically have closer relationships with their parents and receive greater parental attention, both in terms of time and financial investment in their education, as they do not need to share these resources with siblings (reviewed by Y. Liu & Jiang, 2021). These factors can lead to more parental support and better access to educational opportunities, potentially enhancing scientific knowledge in only children. Additionally, our study observed that students' scientific knowledge scores demonstrated statistically significant differences based on their mothers' educational level and occupation. This finding differs from that of a study of German secondary school students, which found that fathers' educational level and occupation, rather than mothers,' had an impact on students' scientific achievement (Steinmayr et al., 2012). While it is true that in Germany, as in other Western societies, mothers traditionally bear primary responsibility for childcare, recent shifts toward shared parenting in these societies have increased the father's role in the family (Milkie & Denny, 2014). In contrast, traditional family roles are still prevalent in China, where mothers are primarily responsible for childcare while fathers focus on providing financial support – a cultural norm that remains widespread despite the impact of globalization (Li et al., 2024). Therefore, in Chinese families, mothers may continue to have a more pronounced influence on their children's academic performance compared to fathers. Interestingly, the research hypotheses regarding motivation in scientific creativity, divergent thinking, and convergent thinking were largely rejected. Only children from affluent families exhibited stronger motivation to engage in scientific creativity than those from average or less affluent families. While all students can receive regular educational activities at their schools, some students from affluent families can participate in more and better-quality extracurricular activities (An & Western, 2019; M. Tan et al., 2021), which can stimulate students' willingness to express their creativity (Castillo-Vergara et al., 2018). However, the overall undifferentiated performance across gender and family background suggests that all students have comparable creative potential in science learning.

With regards to the third research question regarding the relationships among the components of scientific creativity, this study yielded three key findings. First, the results confirmed the hypothesis that divergent and convergent thinking mutually promoted each other, aligning with previous studies (de Vries & Lubart, 2019; Yang et al., 2019). This highlights the importance of convergent thinking in promoting divergent thinking, suggesting that in cultivating students' scientific creativity, educators can encourage students to evaluate and synthesize their ideas after generating diverse and original ones. As de Vries and Lubart (2019) suggested, training students to integrate and synthesize concepts enhances the originality of their scientific ideas. Secondly, extrinsic motivation in scientific creativity was observed to have a statistically significant negative effect on divergent thinking, which contradicts the initial hypothesis, but a comparable finding has also been reported in other studies (Cooper & Jayatilaka, 2006; Xue et al., 2020). A possible explanation for this result lies in the self-reported motivation instrument used in our study, which provided a focused and precise indication of participants' motivation level for scientific creativity, compared to general extrinsic motivation for learning (Wang et al., 2021). Consequently, when students demonstrate scientific creativity with the intention of satisfying others' expectations or obtaining prestige, their divergent thinking is likely to be inhibited rather than enhanced. Lastly, the findings partially support the hypothesis that scientific knowledge positively influenced convergent thinking but revealed limited effects on divergent thinking. This aligns with the findings of Xu et al. (2024), who suggested that assessment of scientific knowledge is based on general school examinations, rather than being designed to support divergent thinking tasks. A similar situation may explain the weak association between scientific knowledge and divergent thinking observed in this study. However, current school examinations often assess students' ability to explain experimental processes and analyze problems critically (The State Council of the People's Republic of China, 2023), which are more closely related to convergent thinking. This may help explain the positive influence of scientific knowledge on convergent thinking observed in this study.

Limitations and future directions

This study has several limitations. First, it was conducted in a single school in China, so while the findings can provide insights into educational practices in similar urban settings across China, they are not necessarily generalizable to all Chinese students. Future research could expand the sample size or explore different regions, such as rural areas, to strengthen the validity and broader applicability of the results. Furthermore, some creative tasks in the C-SCA draw on scientific knowledge from Chinese secondary science textbooks or local environments (e.g., the Chinese sturgeon in Task 1). Researchers working in different educational settings or countries should consider adapting these tasks to ensure their appropriateness for participants' educational levels and cultural backgrounds.

Conclusions

This study provides evidence that our modification of the C-SCA instrument is valid for measuring scientific creativity among secondary school students. The clear scoring process enhances the objectivity of the scientific creativity measurement, and the categorization results generated by our study can be used by subsequent C-SCA users, thereby reducing the time and effort they need to expend.

This study further underscores the superior performance of males and only children in scientific knowledge, coupled with the positive motivation observed in children from affluent families. It also highlights the need for educators to direct more attention toward females and those with siblings in the context of science learning, at least in the Chinese context. Additionally, greater encouragement should be provided to children from less affluent families to enhance their confidence and foster their creativity in science. Given that no significant differences were observed in either divergent or convergent thinking performance across demographic variations in this study, science educators should recognize that all students possess the potential for creativity in science education. Additionally, the role of mothers is crucial in supporting Chinese students' science learning, and this contribution should be acknowledged.

Our study also sheds light on the relationships among the components of scientific creativity, indicating that science educators should focus on fostering the synergistic effects of divergent and convergent thinking, as well as emphasizing the importance of scientific knowledge. In addition, the negative effect of extrinsic motivation reminds educators that high expectations and material rewards may be unhelpful for scientific creativity, and alternative approaches should be employed to foster it.

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Data availability statement

The anonymized dataset used for the analyses in this study is accessible through the UCL Research Data Repository at https://doi.org/10.5522/04/27812928.v1.

Ethics approval and consent to participate

The study is compliant with ethical standards. Approval was obtained from University College London (Z6364106/2023/08/23 social research). The participants were informed about the study, participation was voluntary, and their consent was obtained.

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