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THE CRITICAL YET OVERLOOKED SPATIAL COMPETENCE IN LEARNING ASTRONOMY: DECODING SEMANTIC SPATIAL INFORMATION IN PICTURES

Yi-Chun Chen

Abstract. *This study examined the impact of spatial ability on science achievement by distinguishing between domain-general and domain-specific spatial abilities, focusing on their relationship with the conceptual understanding of the apparent path of the sun. Additionally, the mediating effects of domain-specific spatial knowledge on the relationships between spatial ability and science achievement were tested. A mixed-methods design was used. Forty university students participated. Mental rotation and astronomical drawing tests were used to evaluate their general spatial ability and science achievement. The domain-specific spatial knowledge used in solving astronomical drawing tests was ascertained via interviews and analyzed, with results presented as static-type semantic spatial propositions and dynamic-type spatial skills. The results demonstrated an overlap between general spatial ability and domain-specific spatial knowledge, challenging the traditional dichotomy between them. Furthermore, domain-specific spatial knowledge fully mediated the relationship between general spatial ability and science achievement. These findings have significant implications for astronomy education, highlighting the importance of domain-specific spatial competence over general ability in solving domain problems and underscoring the need for explicit instruction in the decoding of semantic spatial information in pictorial representations, which is often overlooked in studies focusing on spatial skills training or the surface characteristics of scientific representations.*

Keywords: *spatial ability, domain generality, domain specificity, semantic spatial knowledge, astronomy education*

Yi-Chun Chen
National Taiwan Ocean University, Taiwan

Introduction

Promoting conceptual understanding and improving science learning achievement in key science topics is a primary focus of science education (Demkanin, 2023). Many scientific concepts require visualization aids to facilitate understanding. With the advancement of digital technology, the media used in presenting instructional materials have become more diverse (e.g., text, images, animations, and virtual reality displays). The role and benefits of multiple representations have received attention and discussion in science education research (Ainsworth, 1999), as they are believed to improve the quality of teaching and learning in science-related subjects. However, empirical studies have presented inconsistent findings. A review paper by Renkl and Scheiter (2017) noted that multiple representations do not always improve learning. Rau (2017a, 2017b) proposed that learners face a 'representational dilemma,' which refers to the difficulty of comprehending complex scientific knowledge through multiple representations. This dilemma highlights the importance of understanding the meaning that representations are intended to convey. In facing this dilemma, it is suggested that learners' representational competencies be enhanced, yet few studies have explicitly explained the causes from a cognitive perspective. To this end, the current study aims to clarify this phenomenon by examining and comparing the cognitive processes of experienced teachers and students, particularly their knowledge-retrieval states when solving astronomy problems. The knowledge retrieved and stored in long-term memory for solving the problem is organized as declarative knowledge and procedural knowledge (i.e., semantic spatial propositions and spatial skills) for further discussion.

With respect to the theoretical background of teaching or learning science, science educators (e.g., Demkanin et al., 2022; Demkanin, 2023; Osborne, 2014) have suggested applying new perspectives on how humans learn, such as those from neuroscience, cognitive psychology, cognitive sciences, and learning sciences, to enhance learning. Empirical studies exploring the cognitive processes of learning multiple representations have mostly drawn on the well-established cognitive theory of multimedia learning (Mayer, 2014), the integrated model of text and picture comprehension (Schnotz, 2014), and cognitive load theory (Paas & Sweller, 2014). These theories have proposed several general principles of multimedia design.

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For example, the signaling principle (or cueing principle) indicates that highlighting key information enhances learning. However, Chen et al. (2020) have argued that although science learning materials feature a variety of representations, learning science is not simply equivalent to multimedia learning. Unlike graphical representations in engineering and mechanics texts and materials, which primarily depict spatial relations, scientific graphics that represent abstract concepts involve numerous conventions (Hegarty et al., 1991). Scientific images and symbols, such as scientific models, are constructed and simulated by scientists. They do not aim to be realistic depictions or simplified versions of reality. Instead, they serve as a communication medium within the scientific community, carrying specific representational meanings and functions that reflect the norms and scientific language used by this community. For example, although it is well known that the Earth orbits the sun, the celestial sphere model is a well-developed scientific model that adopts an Earth-centered (i.e., geocentric) frame of reference. This model is fictional, but it remains instrumental in explaining and predicting the apparent motions of most stars and the sun, as seen by observers on Earth (Chromey, 2016). Since scientific visualizations are not ordinary pictures and do not always aim to depict reality, the mechanism of science learning may not fully align with theories about multimedia learning. These theories do not address the effects of prior knowledge and do not involve the content of materials, offering only generic principles for designing learning materials with multiple representations. This study selected celestial motion, a complex and important topic in astronomy education, as the research content to reveal the special characteristics of scientific visualizations and explore the influences of domain knowledge.

Owing to the scientific representations being visual-spatial types, spatial ability is considered an important cognitive ability that influences the learning of scientific concepts (e.g., Cole et al., 2018; Newcombe & Shipley, 2015; Sudatha et al., 2018; Uttal & Cohen, 2012). After reviewing empirical studies, Chen et al. (2020) proposed two types of spatial abilities: domain-general and domain-specific spatial abilities. General spatial ability is closely linked to the visuospatial sketchpad system and the central executive function of working memory, whereas domain-specific spatial ability is a competence that combines domain spatial knowledge, including semantic spatial propositions and spatial skills, to solve domain problems. Furthermore, Chen et al. (2020) have argued that domain-general and domain-specific spatial abilities overlap. Although grounded in cognitive psychology and information-processing theory, the claims of the Chen et al. (2020) differ from those of multimedia learning theory in two aspects. One is that multimedia learning theory does not consider the interplay of prior knowledge and excludes context (Cook, 2006; Duschl & Hamilton, 2011). In addition, Paas and Sweller (2014) divided knowledge into biologically primary and secondary categories, suggesting that biologically primary knowledge, as innate knowledge, cannot be transferred through learning, whereas secondary knowledge can be explicitly taught. This division suggests that innate knowledge cannot be cultivated through the acquired environment. Exploring these issues in real science problems will shed light on learning theory and suggest pedagogical methods that are more applicable to science education in a multimedia environment.

Understanding and grasping the concept of celestial motion, a key idea in astronomy (Plummer, 2014), requires spatial thinking, such as mental rotation skills and the ability to switch between different perspectives—the perspective from the Earth's surface and the perspective of the universe looking at the Earth (Cole et al., 2018; Cole et al., 2015; Plummer, 2014; Plummer et al., 2016)—and involves many spatial science concepts (e.g., elevation angle, meridian, latitude). In the celestial sphere model, from a geocentric perspective, the sun revolves around the Earth. This perceived movement, where the sun travels from east to west across the zenith, is called the 'apparent path of the sun.' The variations in this path across different seasons are due to the tilt of the Earth's axis relative to its orbit around the sun, and the apparent path of the sun differs for observers situated at different latitudes on a given date. This study took the complex scientific concept of the apparent path of the sun as the topic to explore the associations among domain-general spatial abilities, domain-specific spatial abilities, and science achievement. It focused especially on testing the mediating effects of prior knowledge on the relationships between general spatial ability and science achievement and justifying the overlap between domain-general and domain-specific spatial abilities according to the model proposed by Chen et al. (2020). It aims to provide valuable insight to improve teaching and learning materials and instruction in science-related topics involving scientific models that require spatial understanding.

Spatial Ability

Generally, spatial ability includes manipulating, visualizing, identifying, capturing, searching for, and locating objects in a spatial context (Carroll, 1993). The discovery of spatial ability can be traced back to Spearman (1927), who used the factor analysis method to confirm that spatial ability is an independent factor in cognitive ability.

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More recently, the Cattell-Horn-Carroll (CHC) model of intelligence has been formulated to provide a comprehensive model of human cognitive abilities, in which spatial ability is called visual processing (Gv) (McGrew, 2009; Schneider & McGrew, 2012). However, there is still no consensus on the subfactors of spatial ability, and the boundaries between them remain unclear (Carroll, 1993; Hegarty & Waller, 2005); this is probably because exploratory factor analysis has the limitation that the spatial ability factor based on psychometric construct validity may not truly reflect the actual use of spatial ability in a psychological test (Hegarty & Waller, 2005). Researchers have attempted to define spatial ability in other ways to establish a close link with performance or behavior when solving real-world problems. For example, Hegarty et al. (2002) stated that the ability to process environmental spatial scales (e.g., applying a sense of direction when driving) differs from the ability to process physical spatial scales. They differentiated spatial abilities into large-scale and small-scale categories and developed a self-report scale specifically for assessing large-scale spatial abilities. It was suggested that this scale could reflect spatial abilities in an environmental situation more accurately than traditional paper-based spatial ability tests. By interviewing people with expertise in different fields, they subsequently reported that scientific disciplines are more closely related to small-scale spatial ability (Hegarty, Crookes, et al., 2010). In summary, studies no longer rely solely on the results of statistical factor analysis but have paid more attention to applying spatial ability in real-life situations. This study used the mental rotation test to assess general spatial ability and compare its effects on achievement in science to those of domain-specific knowledge. The mental rotation test has been categorized as a spatial visualization factor and is widely recognized (Carroll, 1993; Lohman, 1988; McGrew, 2009); Newcombe and Shipley (2015) categorized it as an intrinsic-dynamic spatial skill, which is closely associated with success in STEM fields and is considered most relevant to science learning achievement (Chen et al., 2020; Newcombe & Shipley, 2015).

The Domain-Generality or Domain-Specificity of Spatial Ability for Science Achievement

Spatial ability is not only a theoretical concept but also a crucial factor in learning various science-related disciplines, such as chemistry (e.g., Dickmann et al., 2019; Stieff et al., 2014; Wu & Shah, 2004), biology (e.g., Kong & Olimpo, 2024; Kragten et al., 2015), astronomy (e.g., Cole et al., 2015; Wang & Tseng, 2020), physics (e.g., Kozhevnikov et al., 2007; Wang et al., 2017), and geography (e.g., Hambrick et al., 2012; Ishikawa, 2013; Sanchez & Wiley, 2014). Chen et al. (2020) suggested that spatial ability should be divided into domain-general and domain-specific abilities, where the latter refers to the ability to apply domain-specific spatial knowledge, including spatial-type static declarative knowledge and dynamic procedural knowledge. Cho and Suh (2019) expressed similar opinions. They argued that general spatial ability cannot measure the skills needed for interior design and developed a domain-specific spatial ability test. The results showed that domain-specific spatial ability in interior design was more closely related to the originality and quality of the design and that men outperformed women only in general spatial ability. Studies using specific spatial skills, which are necessary for solving domain problems, have revealed significant correlations with performance in science (e.g., Merchant et al., 2012; Ozdemir, 2010). Furthermore, research has revealed that several specific spatial skills, not all, are related to science achievement (e.g., Ishikawa, 2013; Sanchez & Wiley, 2014), that spatial ability still has strong associations with learning outcomes even after training (e.g., Keehner et al., 2006), or that it has stronger effects on older students than younger ones (e.g., Yan et al., 2023). These findings indicate the existence of domain specificity. On the other hand, the effects of spatial ability on science achievement, particularly the spatial visualization factor, are likely to be inherently general because of their strong connection to the central executive functions of working memory (Chen et al., 2020). Support for this idea is obtained from the significant correlation between spatial ability and word-based performance (e.g., Tolar et al., 2009; Zhang et al., 2017) or social sciences (e.g., Nolte et al., 2024). Researchers have suggested that spatial ability affects early learning performance more. As people acquire knowledge, the need for spatial ability gradually weakens (Hambrick et al., 2012; Keehner, 2011; Uttal & Cohen, 2012). This suggests that spatial ability is domain-general because it does not involve domain knowledge. The above review suggests that spatial ability has both general and specific effects on science achievement. Chen et al. (2020) have argued that it is essential to differentiate between domain-general and domain-specific spatial ability to understand and discuss their separate effects on science achievement. This was one of the purposes of this study.

Relations between Domain-General and Domain-Specific Spatial Abilities

The traditional psychological perspective has often posited that general and specific abilities (such as the ability to apply domain knowledge) are distinct. For example, CHC theory delineates spatial ability (Gv) and domain-

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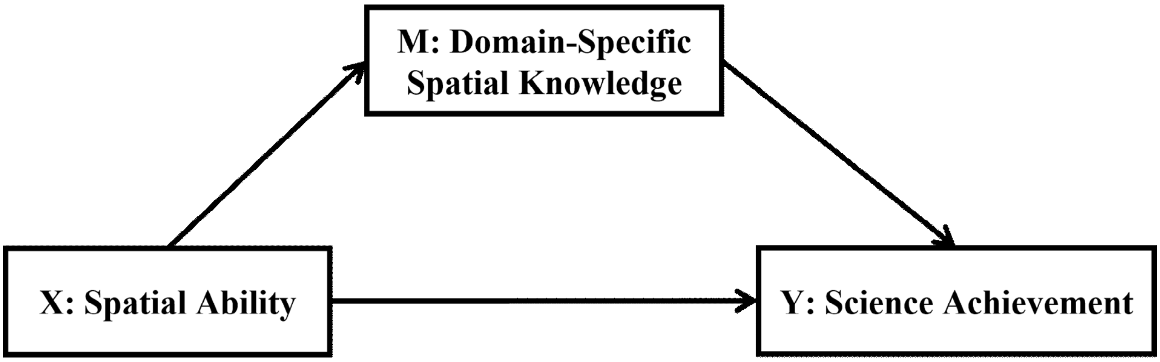
specific knowledge (Gkn) as separate factors (McGrew, 2009; Schneider & McGrew, 2012). Sorby (1999) defined spatial ability as innate and spatial skills as developed through training. Cole et al. (2018) reviewed spatial ability assessments in astronomy education and categorized the assessments into domain-general (e.g., block rotation, paper folding) and domain-specific (interviews, astronomy concept tests) spatial abilities. However, Chen et al. (2020) have argued that domain-general and domain-specific spatial abilities overlap with identical spatial skills rather than being dichotomous. This is supported by the skill-overlap hypothesis (Singley & Anderson, 1989), which suggests that tasks involving similar mental operations allow for skill transfer. Recent cognitive neuroscience research (Wang et al., 2022) using functional magnetic resonance imaging (fMRI) has shown that understanding physical and chemical principles activates both semantic and visuospatial networks, challenging the traditional separation of spatial ability and semantic domain knowledge. Schunn and Anderson (1999) proposed that skills range along a continuum from general to specific, blurring the line between domain-general and domain-specific spatial abilities. Expertise requires a long period of deliberate practice to develop (Ericsson et al., 1993). Corresponding to the degree of skill mastery, Hoffman (1998) proposed that the proficiency scale from naive (completely ignorant of a domain) to master has seven levels. In real-life situations, most people with basic public education, who fall between novices and experts, require a combination of learned declarative and procedural knowledge to solve or reason about various problems. These types of knowledge, referred to as competencies, lie between natural general abilities and advanced expertise (Sternberg & Grigorenko, 2003). Competencies are the specific skills and knowledge individuals acquire through learning and practice and are essential for problem solving and reasoning. Newcombe and Learmonth (2005) introduced the concept of spatial competence, which refers to predicting the outcomes of spatial movements or transformations. Humans possess two unique spatial competencies: the ability to use symbols to convey spatial properties (such as visual–spatial symbols, maps, models, and spatial language) and the ability to reason and solve problems through spatial representations and spatial thinking. Demkanin et al. (2022) suggested that the necessary spatial competencies in science education include using symbols and identifying patterns, orders, categories, and relationships. Chen et al. (2020) proposed domain-specific spatial ability as a competence that combines domain-specific spatial knowledge and skills, which can better predict science learning outcomes and can be cultivated. This study uses the scientific context of the sun's apparent path to provide empirical evidence to support and elaborate on the claims that the specificity of spatial ability and domain-specific spatial ability overlap with general spatial ability.

The Mediating Role of Domain-Specific Spatial Knowledge in the Relationships between Spatial Ability and Science Achievement

General spatial ability is the foundation for developing domain-specific spatial ability (Gagné et al., 1993); both influence learners' science achievement. For learners with acquired knowledge, domain-specific knowledge exerts a greater impact on science achievement than does general spatial ability (Chen et al., 2020; Hambrick et al., 2012; Keehner, 2011; Uttal & Cohen, 2012). On the basis of the above review, Figure 1 illustrates a hypothesized mediation model in which domain-specific spatial knowledge, as the mediator, influences the relationship between general spatial ability and science achievement. One of the purposes of this study was to test this model.

Figure 1
Hypothesized Mediation Model of This Study



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Current Study and Research Questions

Using the topic of the apparent paths of the sun as the context, the study had two main objectives. First, I compared the effects of domain-general and domain-specific spatial abilities on science achievement and explored the overlap between the two spatial abilities. Second, the mediating effects of domain-specific spatial knowledge on the relationships between general spatial ability and science achievement were tested. The four research questions were as follows.

RQ1: To what extent is general spatial ability related to science achievement?

RQ2: To what extent is domain-specific knowledge related to science achievement?

RQ3: In what way do general spatial ability and domain-specific knowledge overlap?

RQ4: Is there a significant mediating effect of domain-specific spatial knowledge on the relationships between spatial ability and science achievement?

Research Methodology

General Background

This study employed a mixed-methods design. Forty university students voluntarily participated after school hours. The quantitative data included general spatial ability, science achievement, and domain-specific spatial knowledge. The correlations between the variables were analyzed, and the mediating effects of domain-specific spatial knowledge were examined. The three-dimensional mental rotation test was used to assess the students' general spatial ability, and the astronomical drawing test was used to assess science achievement on the topic of the apparent path of the sun. The problem-solving processes of the astronomical drawing test were explored through semistructured interviews. Using content analysis, the responses of 12 in-service teachers about the knowledge retrieved when drawing the apparent path of the sun were analyzed and categorized as declarative knowledge (semantic spatial propositions) and procedural knowledge (spatial skills) to elaborate on the attributes of domain-specific spatial knowledge and qualitatively discuss its overlap with general spatial ability. The categorized semantic spatial propositions and spatial skills served as criteria for accurate domain-specific spatial knowledge. The students' interview data were analyzed and scored based on these criteria. The students were required to complete the test in the following order: the mental rotation test, the astronomical drawing test, and the interview. All test questions were answered at each individual's own pace. Depending on the individual, the experimental procedure took approximately 30–40 minutes for the teachers and 40–50 minutes for the students.

Participants

A total of 40 first- and second-year university students (aged between 17 and 20) recruited through the Internet voluntarily participated in this study. Before their involvement, online announcements informed participants about the research aims. Once they confirmed their participation, they were given a detailed briefing on the experimental procedures, assessment tasks, and interviews. They could withdraw anytime, but no one chose to do so. The participants were assured that no personal information would be disclosed and that they would receive approximately $10 as compensation upon experiment completion. They were not earth science majors at the university but had taken introductory earth science courses in upper-secondary school. They had learned the basics of reasoning about the sun's apparent path at different latitudes. On the proficiency scale, these students were at the 'initiate' level, which is defined as "someone who has been through an initiation ceremony—a novice who has begun introductory instruction" (Hoffman, 1998, p. 84). Slightly over half were majors in social sciences or humanities (10 males and 11 females), and the others were majors in natural sciences or engineering (9 males and 10 females). Additionally, 12 in-service teachers (6 females) who teach earth sciences in public upper-secondary schools were invited. Eleven had a Master of Science degree, and their teaching experience ranged from 1 to 10 years (*M* = 6.25, *SD* = 2.67). To obtain the Earth Science Teaching Certificate, one must pass three compulsory courses at the university level: astronomy, astronomical observation, and astronomical observation practices. The teachers were proficient in the subject matter, pedagogical content knowledge, and oral expression skills and had an understanding of students' learning status and the content of current textbooks. Consequently, they were more qualified than academic experts to serve as participants.

Measures

a. Spatial ability

The Purdue Visualization of Rotations Test (Bodner & Guay, 1997) was used to assess three-dimensional mental rotation spatial ability. The students observed the same object both before and after it had been rotated, taking note of the directions and angles of rotation. They then applied these observations to a new geometric object to select the only correct answer. The rotated geometric objects in the Purdue Visualization of Rotations Test can be divided into four levels of difficulty: Type I: rotated 90° around one axis; Type II: rotated 180° around one axis; Type III: rotated 90° around one axis and rotated 90° again around another axis; and Type IV: rotated 90° around one axis and rotated 180° again around another axis (Chen & Yang, 2014). The larger the level number is, the more complex the rotation. A total of 12 items were selected, with three items of each type. Each item was presented in a multiple-choice format, and the highest possible score was 12.

b. Science achievement

A paper-based astronomical drawing test was employed to assess students' science learning achievement, indicating the extent to which they understood the subject matter of the sun's apparent motion. I developed this test in collaboration with two experts in geosciences and astronomy, one of whom held a Ph.D. in the latter subject. In contrast to multiple-choice questions, astronomical drawing tasks permit students to externalize their internal mental models of the sun's apparent paths on paper, thereby more precisely revealing the degree of their conceptual understanding of this complex target topic. The astronomical drawing test, designed to be internationally applicable regardless of language background, consisted of four tasks with four blank hemispheres that were marked only east, west, north, and south. The participants were asked to draw the sun's apparent paths on the date of the summer solstice (approximately June 21) at four different latitudes: 23.5°N, 60°N, 23.5°S, and 60°S.

In the standard high school textbook on earth sciences in Taiwan, the basic concepts of celestial motion are introduced, along with a discussion of the sun's apparent path. On the day of the summer solstice, 23.5°N (also the location of Taiwan) is the northernmost position the sun can reach in a year. Therefore, drawing the apparent path of the sun at 23.5°N at the summer solstice holds significant meaning, which could be used to assess students' basic understanding of this concept. The students likely knew that polar days and nights occur at latitudes north of the Arctic Circle and south of the Antarctic Circle. They were less familiar with understanding the remaining latitudes, particularly those different from where they lived. Science achievement in this study indicate students' near transfer performance. Near transfer is 'Much overlap between situations; original and transfer contexts are highly similar' (Schunk, 2012, p. 319). It was necessary for students to use existing knowledge to infer the apparent path of the sun at other latitudes. For example, at the summer solstice, the sun's position at noon had a solar declination of +23.5° (meaning the sun is directly over 23.5°N latitude). At different latitudes, students had to visualize the sun's relative position in the sky to determine its position.

The four drawings at different latitudes were each scored according to the following criteria: the position of the sun at noon (1 point), the position of the sun at sunrise (and sunset) (1 point), the direction of inclination (0.5 points) and the angle of inclination (0.5 points). The highest possible score was 12. Figure 2 (the bold red line) shows the correct answer for 23.5°N. The appendix provides the correct answers for the other latitudes (i.e., 60°N, 23.5°S, and 60°S).

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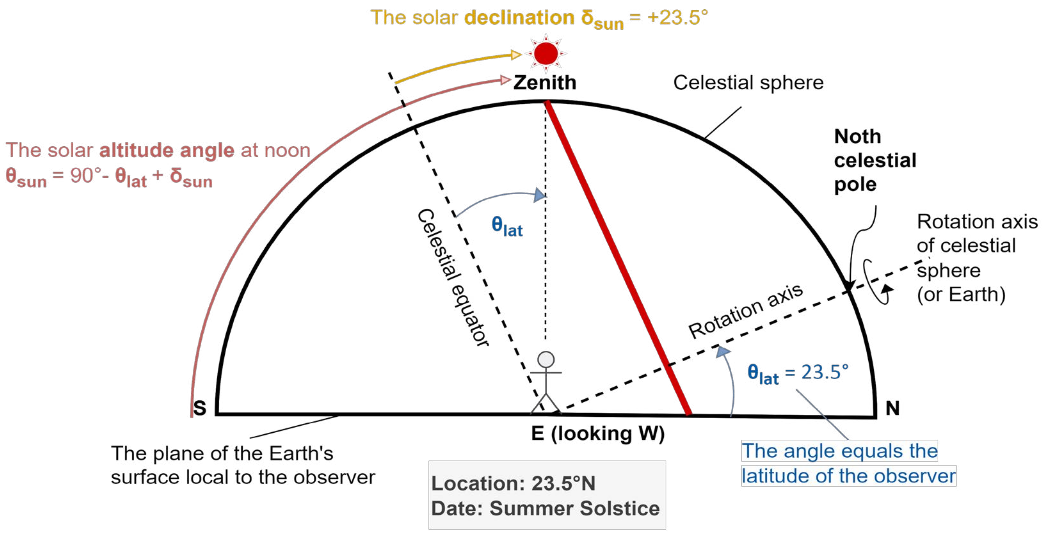
Figure 2

Apparent Paths of the Sun at the Summer Solstice (Approximately June 21) at 23.5°N



c. Domain-specific spatial knowledge

Domain-specific spatial knowledge stored in long-term memory cannot be directly observed. This study presented participants with actual problems (a drawing test) in astronomy and interviewed them about the processes of solving problems to analyze their stored knowledge. This study defined domain-specific spatial knowledge as comprising two parts: semantic spatial propositions and spatial skills for indicating declarative and procedural knowledge.

According to cognitive theories, knowledge structures can be divided into declarative knowledge and procedural knowledge (Anderson, 1983, 2020; Gagné et al., 1993). Declarative knowledge represents static factual information. The forms of declarative knowledge are still controversial, although they probably include images (see the dual coding theory proposed by Paivio, 1971); in this study, conceptual–propositional theory (Anderson & Bower, 1973; Pylyshyn, 1973, 1984, 2006) was used to analyze and represent the participants' declarative knowledge. In conceptual–propositional theory, a proposition is the basic unit of static knowledge and expresses relationships among concepts that can be judged as correct or incorrect in concrete cases (Anderson & Bower, 1973; Gagné et al., 1993). Using the content analysis method, the knowledge retrieved by the teachers while performing the astronomical drawing test was represented in the propositional form shown in Table 1, which was used as a coding scheme to score student responses. The propositions are abstract and represent ideas but not exact words (Gagné et al., 1993). Students' expressions, including assistance in answering via gestures or drawings, were scored as one point if the meaning was correct (i.e., corresponding to one of the propositions in Table 1). The highest possible score on the semantic spatial propositions was 6. In this study, declarative knowledge was called 'semantic spatial' propositions for the following reasons. First, the problem-solving task, which involved drawing the sun's apparent path, was pictorial with no concrete words, so the propositions involved the 'semantic' knowledge implied by the pictures. Second, the propositional representations used a 'predicate' to represent the relationships among 'arguments'; this representation is known as 'predicate calculus' (Anderson, 2020; Gagné et al., 1993). As shown in Table 1, all six predicates of the propositions are 'spatial' attributes, representing spatial relationships (please refer to Figure 2 and the Appendix for further details.).

In contrast, procedural knowledge is dynamic. It refers to the knowledge of how to perform an action (then…) under a specific condition (if...), represented by a sequence of IF-THEN pairs called productions (Gagné et al., 1993). Table 2 shows two productions proposed by the teachers, who used different strategies to solve problems of drawing the apparent paths of the sun at different latitudes. The verbs of the two productions, 'rotate' and 'translate' (move the path a certain distance), are spatial attributes, which are the actions taken after understanding the relevant declarative knowledge (i.e., SP1, SP4, SP5, and SP6 in Table 1) and are called domain-specific spatial skills. The problems could be solved in both ways, so the two independent spatial skills and their correlations with other spatial skills and science achievement were examined. The sum of the declarative knowledge (6 semantic

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spatial propositions) and procedural knowledge (2 spatial skills) scores was the total score of domain-specific spatial knowledge, which was 8 points for examining the mediating effect of domain-specific knowledge on the relationships between spatial ability and science achievement. Tables 1 and 2 were reviewed by an experienced high school teacher (with 12 years of teaching experience) and an astronomy expert (with a PhD degree and more than five years of postdoctoral experience in astronomy and academic publications).

Table 1
Semantic Spatial Propositions Retrieved by Teachers

Code	Semantic Spatial Propositions
SP1	At the spring/fall equinox, the sun rises from the due east (and sets from due west) (everywhere on the Earth) **DUE EAST [spatial position]** (SUNRISE [object], SPRING/FALL EQUINOX [date])
	At the summer solstice, the sun rises (and sets) from the northeast (everywhere on the Earth). **NORTH-EAST [spatial position]** (SUNRISE [object], SUMMER SOLSTICE [date])
SP2	The two apparent sun paths at the spring/fall equinox and summer solstice are parallel. **PARALLEL [spatial relation]** (SUN'S APPARENT PATHS [object], SPRING/FALL EQUINOX [date], SUMMER SOLSTICE [date])
SP3	The elevation angle of Polaris [the north celestial pole] is numerically equal to the observer's local latitude. **NUMERICALLY EQUAL [numerical/spatial relation]** (OBSERVER [subject], ELEVATION ANGLE OF POLARIS/NORTH CELESTIAL POLE [object], LOCAL LATITUDE [location])
	The elevation angle of the south celestial pole numerically equals the observer's (local) latitude. **NUMERICALLY EQUAL [numerical/spatial relation]** (OBSERVER [subject], ELEVATION ANGLE OF SOUTH CELESTIAL POLE [object], LATITUDE [location])
SP4	The sun's apparent path is perpendicular to the Earth's celestial axis. **PERPENDICULAR [spatial relation]** (SUN'S APPARENT PATH [subject], EARTH'S/ CELESTIAL AXIS [object])
SP5	At the summer solstice, the sun is directly over 23.5°N latitude. **DIRECTLY OVER [spatial relation]** (SUN [subject], 23.5°N LATITUDE [object, location], SUMMER SOLSTICE [date])
	At the summer solstice, the solar declination (δ_{sun}) is numerically equals +23.5°. **NUMERICALLY EQUAL [numerical relation/spatial relation]** (SOLAR DECLINATION (δ_{sun}) [subject], +23.5° [angle], SUMMER SOLSTICE [date])
	At the summer solstice, the sun is directly overhead at noon at 23.5°N latitude. **DIRECTLY OVERHEAD [spatial relation]** (SUN [subject], NOON [time], 23.5°N LATITUDE [object, location], SUMMER SOLSTICE [date])
SP6	The solar altitude angle at noon numerically equals 90° minus the observer's latitude plus the solar declination. ($\theta_{sun} = 90^\circ - \theta_{lat} + \delta_{sun}$) **NUMERICAL RELATION [numerical relation/spatial relation]** (SOLAR ALTITUDE ANGLE (θ_{sun}) [subject], 90° [angle], OBSERVER'S LATITUDE [location, angle], SOLAR DECLINATION (δ_{sun}) [angle], NOON [time])
	The solar zenith angle at noon numerically equals the observer's latitude minus the solar declination. ($\varphi_{sun} = \theta_{lat} - \delta_{sun}$) **NUMERICAL RELATION [numerical relation/spatial relation]** (SOLAR ZENITH ANGLE (φ_{sun}) [subject], OBSERVER'S LATITUDE (θ_{lat}) [location, angle], SOLAR DECLINATION (δ_{sun}) [angle], NOON [time])

Note. The semantic conceptual knowledge retrieved by the teachers was represented by the more shorthand propositional form: **PREDICATE [spatial relationship]** (ARGUMENTS [subject], [object], [angle], [time], [date], [location], [location, angle]). SP, Spatial Proposition.

Table 2
Domain-Specific Spatial Skills and Productions Retrieved by Teachers.

Code	Domain-Specific Spatial Skills and Productions
SS1	**Rotating around the Earth's axis**
	IF Goal is to draw the sun's apparent path at the summer solstice date. THEN (After determining the sun's position in the sky at noon by using SP5 or SP6) Draw the apparent path of the sun by **rotating the sun around the Earth's axis**.

Code	Domain-Specific Spatial Skills and Productions	
SS2	**Translating the sun's apparent path**	
	IF	Goal is to draw the sun's apparent path on the summer solstice date.
	THEN	(After determining the sun's apparent path at the date of spring/fall equinox by using SP1 and SP4) Draw the apparent path of the sun by **translating the sun's apparent path** with a central angle of 23.5° toward the North.

Note. SS, spatial skill; SP, spatial proposition.

Interview

The cognitive processes involved in spatial reasoning while drawing the four apparent paths of the sun were explored through semistructured interviews, allowing for more flexible questioning based on the participants' responses. The interviews were conducted by the researcher, an earth sciences major with a PhD in science education and at least four years of secondary school teaching experience.

Both teachers and students were asked to answer the central question: "How do you solve the problems of the apparent paths of the sun?" Depending on whether the participants could answer fluently, two situations were distinguished:

1. If the participants could answer fluently, the reviewers moved on to the question: "Do you have a set of regular and general procedures for answering such questions?" If the answer was YES, the participants were asked to describe the strategies. If the answer was NO, they were asked to describe the order in which they had drawn the four figures with different latitudes and why.
2. If the participants could NOT answer fluently, they were asked first to focus on the representative latitude, 23.5°N, and describe how they had drawn it. The following latitudes were then described in order: 60°N (same hemisphere but different latitudes), 23.5°S (same latitude but different hemispheres), and 60°S (both the hemispheres and latitudes were different).

In addition to the two main questions mentioned above, the interviewer also asked participants how they determined position of the sun at noon, how they established the positions of sunrise and sunset, how they determined the angle of inclination of the sun's apparent path. The participants were instructed to examine the differences between two of the four drawings to identify and infer the problem-solving strategies used, and were encouraged to express themselves as much as possible, whether right or wrong, and they could use gestures or drawings to aid their responses if necessary. Depending on the individual, this portion took approximately 15–25 minutes for the teachers and 10–30 minutes for the students.

Procedure

The teachers were asked to complete the task of drawing the sun's apparent paths and were then interviewed. The students completed a spatial ability test before the drawing test and interview. The items on the spatial ability test (the Purdue Visualization of Rotations Test) were presented on the computer screen in a sequence that progressed from simple to complex, with one item shown at a time. The students were instructed to confirm the answer before proceeding to the next item. Once an answer was selected, it could not be revised. All test questions could be answered at the individual's own pace. The experimental procedure took approximately 30–40 minutes (for the teachers) or 40–50 minutes (for the students).

Data Analysis

SPSS 25.0 was used to analyze the data, and the results are presented as descriptive statistics and Pearson correlations with a significance level of .05 (two-tailed). Additionally, the PROCESS macro 4.2 for SPSS (Hayes, 2022) was employed to test the mediating effects of domain-specific spatial knowledge on the relationships between spatial ability and science achievement. The bootstrapping technique was conducted with a relatively small sample size, which increased confidence and statistical power (Hayes, 2022; Hayes & Preacher, 2014). The number of bootstrap resamples for determining the percentile bootstrap confidence intervals (CIs) was set to 5,000. The indirect effect was considered statistically significant if the 95% bootstrap CI did not contain zero.

Research Results

Basic Characteristics

Table 3 shows the means and standard deviations for the measures used in this study. As the complexity of the rotation increased (Type I to Type IV), the mean score (*M*) decreased, and the standard deviation (*SD*) increased. The greater *SD* of the astronomical drawing test revealed that science achievement varied among students more than the other measures did. With respect to domain-specific spatial knowledge, the mean number of semantic spatial propositions retrieved by students was less than half of the total number of correct propositions (2.43 < 3). Among domain-specific spatial skills, students used rotation skills more than translation skills on average when solving scientific spatial problems about the apparent paths of the sun (0.58 > 0.05).

Table 3

Basic Characteristics of the Measures (N = 40)

Measures (Total Scores)	*M*	*SD*
Mental rotation test (12)	8.63	2.23
Type I (3)	2.70	0.52
Type II (3)	2.15	0.89
Type III (3)	2.05	0.96
Type IV (3)	1.72	0.99
Astronomical drawing test (12)	6.51	3.29
Domain-specific spatial knowledge (8)	3.05	2.01
Semantic spatial propositions (6)	2.43	1.55
Rotating the sun around the Earth's axis (1)	0.58	0.50
Translating the Sun's apparent path (1)	0.05	0.22

Table 4 presents the percentages of domain-specific spatial knowledge retrieved by the students. In terms of static spatial knowledge, SP5 (the sun is directly over 23.5°N latitude at the summer solstice) is the most well known, and SP2 (the two apparent sun paths at the spring/fall equinox and summer solstice are parallel) is less often mentioned. Concerning dynamic spatial skills, most students used rotation skills rather than translation skills (only 5%) to solve problems.

Table 4

Percentages of Domain-Specific Spatial Knowledge Retrieved by Students (N = 40)

Domain-Specific Spatial Knowledge	Retrieved Percentage
Semantic Spatial Propositions	
SP1	20
SP2	5
SP3	52.5
SP4	47.5
SP5	75
SP6	42.5
Domain-Specific Spatial Skills	
SS1	57.5
SS2	5

Note. SP, spatial proposition; SS, spatial skill.

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Bivariate Correlations of Critical Variables

Table 5 shows that general spatial ability (assessed by the mental rotation test) is significantly correlated with science achievement (assessed by the astronomical drawing test) ($r = .447$, $p < .01$). However, separate examinations of the relations among the different types of spatial skills and science achievement produced noteworthy results. Among the four types of difficulty, only Type I and Type II were significantly correlated with science achievement, and the correlation coefficient for the latter was greater ($r = .315$, $p < .05$; $r = .456$, $p < .01$, respectively). In answer to the first research question, the results revealed that although the overall mental rotation test scores were correlated with science achievement on the topic of the apparent path of the sun, Type II mental rotation skills (i.e., rotation by 180° around one axis) were more highly correlated than Type I skills (i.e., rotation by 90° around one axis) and were not significantly correlated with complex mental rotation skills involving rotations around two axes.

In regard to the second research question, the results revealed that the relationships between domain-specific spatial knowledge and science achievement were positively correlated ($r = .714$, $p < .001$). Table 5 shows that semantic spatial propositions exhibited the highest correlation with science achievement ($r = .754$, $p < .001$), followed by the spatial skills of rotating the sun around the Earth's axis ($r = .395$, $p < .05$) and translating the sun's apparent path ($r = .318$, $p < .05$). Among the three types of domain-specific spatial knowledge, the spatial skills of rotating the sun around the Earth's axis and translating the sun's apparent paths significantly correlated with semantic spatial propositions ($r = .635$, $p < .001$; $r = .461$, $p < .01$), revealing the close relationships between declarative and procedural knowledge. No statistically significant correlation was found between the two domain-specific spatial skills ($r = .197$, $p = .223$), revealing that these two spatial skills were independent, as expected.

The third research question examined the relationships between spatial ability and domain-specific knowledge, and the results indicated that they were significantly correlated ($r = .508$, $p < .01$). Among the four types of rotation, only Type II (i.e., rotation by 180° around one axis) and Type III (i.e., rotation by 90° around two axes) mental rotation skills were correlated with domain-specific knowledge ($r = .538$, $p < .001$; $r = .331$, $p < .05$, respectively). The semantic spatial propositions correlated significantly with the total scores on the mental rotation test ($r = .515$, $p < .01$), especially with Type II mental rotation skills ($r = .564$, $p < .001$), but they were not found to be statistically significantly correlated with the other types. Concerning the two domain-specific spatial skills, only the score regarding the rotation of the sun around the Earth's axis correlated with spatial ability ($r = .405$, $p < .01$), particularly the moderately difficult spatial rotations of Type II ($r = .318$, $p < .05$) and Type III ($r = .419$, $p < .01$). Translating the sun's apparent paths was not correlated with any type of mental rotation skill. In addition, similar to the results of the relationships between spatial ability and science achievement, although the total mental rotation test scores were significantly correlated with domain-specific knowledge, semantic spatial propositions, and domain-specific spatial skills involving rotation skills, only limited types of rotation were found to be statistically significant.

Table 5
Results of the Pearson Correlation Analysis

Measures	1	I	II	III	IV	2	3	4	5	6
1. Mental rotation test	1									
Type I	.457**	1								
Type II	.764***	.211	1							
Type III	.621***	.083	.290	1						
Type IV	.722***	.237	.426**	.123	1					
2. Astronomical drawing test	.447**	.315*	.456**	.173	.263	1				
3. Domain-specific spatial knowledge	.508**	.237	.538***	.331*	.214	.714***	1			
4. Semantic spatial propositions	.515**	.259	.564***	.296	.229	.754***	.979***	1		
5. Rotating around the earth's axis	.405**	.089	.318*	.419**	.173	.395*	.760***	.635***	1	
6. Translating the sun's apparent path	.091	.135	.221	-.012	-.053	.318*	.514**	.461**	.197	1

*$p < .05$, **$p < .01$, *** $p <.001$ (two-tailed)

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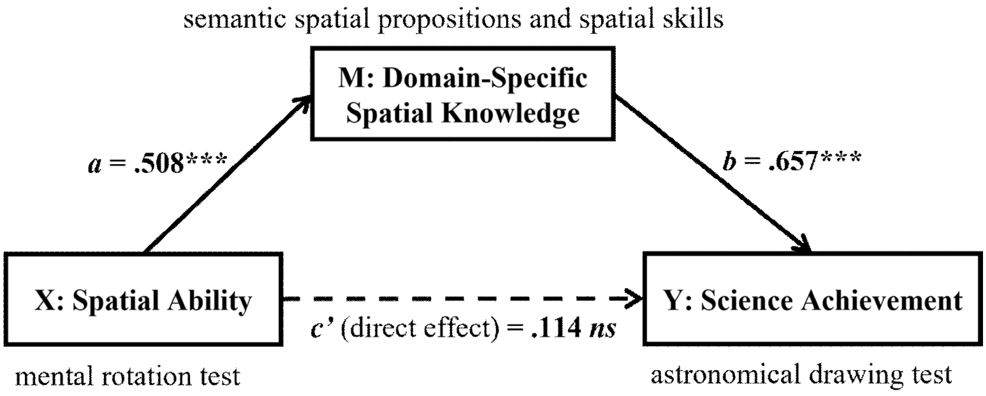
Mediation Analyses

The fourth research question concerned the hypothesized mediation model (Figure 1). Figure 3 and Table 6 show the relevant results. Both paths, from spatial ability to science achievement (path *a*, X→M) and from domain-specific spatial knowledge to science achievement (path *b*, M→Y), were significant ($\beta = .508$; SE = .126, $t = 3.635$, $p < .01$; $\beta = .657$; SE = .216, $t = 4.965$, $p < .001$). The indirect effect (path *c*, X→M→Y) was 0.334 and was significant because the bootstrap 95% CI did not contain zero ([0.713, 0.527]). The direct effect of the mediation model (path *c′*, X→Y) was not significant ($\beta = .114$; SE = .195, $t = 0.858$, $p = .396$). The results indicated that domain-specific spatial knowledge fully mediated the relationship between spatial ability and science achievement. The first path (*a*) suggests that domain-general spatial ability supports the acquisition of domain-specific spatial knowledge, including the development of conceptual semantic propositions and spatial skills. The second path (*b*) indicates that the richness of the knowledge structure stored in long-term memory impacts science achievement in terms of solving scientific problems that require spatial thinking.

Figure 3

The Simple Mediation Model of the Associations between Spatial Ability and Science Achievement through Domain-Specific Spatial Knowledge



****p* < .001 (two-tailed). *ns*: not significant, *p* > .05. All the values have been standardized.

Table 6

Results of the Simple Mediation Model

Standardized values				
Path c	Effects	Boot SE	Bootstrap 95% CI	
Indirect effect (X→M→Y)	0.334	0.091	0.173	0.527

Note. SE, standard error; CI, confidence interval; X, spatial ability; M, domain-specific spatial knowledge; Y, science achievement

Discussion

The Spatial Skills Used for Solving Domain-Specific Problems Are Domain-Specific

With respect to the relations among science achievement, domain-specific spatial knowledge, and spatial ability, only limited subsets were correlated. This finding suggests that the spatial skills used to solve domain-specific problems (with clearly defined goals, specific paths to solutions, and single correct answers) are domain specific, following the perspective presented in my previous study (Chen et al., 2020). The study results showed that science achievement on the topic of the apparent paths of the sun was more strongly related to the specific spatial skills of

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rotation around a single axis by 90 degrees and 180 degrees. This is because, to draw the sun's apparent paths in the actual situation, after locating the position of the sun in the sky through static declarative knowledge, it is only necessary to rotate around a single axis (i.e., the Earth's axis of rotation) by 180 degrees (in a 3D-sphere mental image) or by 90 degrees (on 2D paper). There is no need to rotate around any other axis. Similarly, for domain-specific knowledge, static declarative knowledge is most relevant to 180-degree rotation skills. For dynamic procedural knowledge, only domain-specific skills in the form of rotations, not translations, are mainly used. This study highlights the importance of domain-specific spatial skills in specific science domains, which are performed under the constraints of existing scientific knowledge. Examining the overall spatial ability score obscures important findings: Correlations are found for the specific spatial angles necessary for solving problems within particular domains.

Overlapping Relationships between Spatial Ability and Domain-Specific Spatial Knowledge

This study focused on solving scientific problems requiring spatial thinking to explore the relationships between spatial ability and domain-specific knowledge. Both the qualitative and quantitative results suggest an overlap between general spatial ability and domain-specific spatial knowledge. Taking an important astronomy topic, the sun's apparent path, as an example, spatial skills were related to rotation overlap, particularly rotation around a single axis by 180 degrees. This finding is consistent with our previous hypotheses (Chen et al., 2020): Knowledge for solving celestial motion problems involves spatial attributes. Like novices and experts are placed along a continuum (Hoffman, 1998), general and specific abilities exist on a spectrum. This issue requires further discussion within interdisciplinary research.

Semantic Spatial Knowledge Is More Critical Than Spatial Skills for Science Achievement

Current research has focused primarily on spatial skill training (e.g., Gutierrez et al., 2015; Milkova & Pekarkova, 2023; Uttal et al., 2013) or the effects of static or dynamic representations for learning (e.g., Chen et al., 2015; Wang & Tseng, 2020), overlooking the importance of semantic spatial knowledge. The semantic spatial knowledge of domain-specific knowledge is more critical than the dynamic domain-specific spatial skills for conceptual understanding, particularly in learning astronomy. The importance of decoding semantic spatial information in pictures provides supplementary explanations for why superficial visual salience (i.e., the signaling effect) sometimes does not affect learning, in which Canham and Hegarty (2010) and Hegarty et al. (2010) emphasized the key role of learned knowledge. Previous research (Chen et al., 2020) has provided only a rough outline, called spatial-type scientific declarative knowledge. This study offered a more in-depth explanation, describing spatial-type scientific declarative knowledge as semantic spatial knowledge; semantic spatial knowledge was represented herein by propositions to enable a clearer understanding of its characteristics. The predicates linking the arguments in each proposition have spatial relationships, including the scientific principles or rules in a domain, and therefore have spatial attributes. Semantic spatial knowledge is the scientific language formulated by scientists to enable communication within the scientific community, which is implied in picture-type scientific representations, and it is acquired rather than innate. Because the objects manipulated in psychological assessments are typically in the form of building blocks or paper, which do not involve static spatial-language information, few studies have emphasized the importance of encoding semantic spatial information in pictures in learning science. This requires attention in subsequent research.

Domain-Specific Spatial Knowledge Fully Mediates the Relationships between Spatial Ability and Science Achievement

The results of the mediation model demonstrate that domain-general spatial ability influences science achievement entirely through domain-specific spatial knowledge, which is consistent with the hypothesis model of this study and was previously proposed by Chen et al. (2020). General spatial abilities are a prerequisite for developing domain-specific spatial knowledge, which individuals then use to solve problems. Domain-specific spatial knowledge includes propositions connecting spatial relations among concepts and spatial skills manipulated under constraints by scientific rules or principles. This necessary knowledge for solving domain problems involves spatial attributes, which explains the findings in the literature by Keehner et al. (2006) that there are still close relationships between spatial ability and tasks after training. Domain-specific spatial knowledge is more essential than general spatial ability for scientific conceptual understanding. Educators should prioritize developing

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domain knowledge over general abilities; specifically, the underlying domain principles should be taught explicitly and directly to improve science achievement.

Conclusion and Implications

This study highlights the importance of domain-specific spatial knowledge over general spatial ability with respect to semantic spatial propositions and spatial skills in performance related to specific science domains. Combining static declarative knowledge with dynamic procedural knowledge is regarded as competence, which is cultivable and predictive of learning outcomes. Spatial skills are exercised under constraints corresponding to existing scientific knowledge. However, the semantic spatial knowledge in graphical representations is implicit. In practice, science learning materials and instructions should reveal the semantic information behind scientific representations. It is necessary to explicitly use the corresponding words to describe rather than presuming that they will inherently comprehend these concepts and principles through their innate spatial abilities. Furthermore, it is essential to differentiate between domain-general and domain-specific spatial abilities to avoid confusion, as general ability is traditionally regarded as innate. On the basis of the evidence of significant positive correlations between spatial ability and learning performance in scientific conceptual understanding, it is often claimed that individuals who excel in science do so because of their superior general spatial ability. However, this claim needs to be reconsidered. The fact that the spatial attributes involved in acquired domain-specific knowledge overlap with general spatial abilities supports this finding. Moreover, it is recommended that students be trained in spatial skills within real-world contexts. The effectiveness and necessity of training in general spatial skills are questionable, particularly when more complex rotation angles that are not typically involved or used in real-world scenarios are considered. Finally, the confirmation of the mediating model reveals different instructional focuses between students with high and low spatial abilities. For those with low spatial ability, difficulty exercising general spatial skills may subsequently affect their understanding of spatial concepts and scientific principles and the spatial interconnections between them. Consequently, there is a need for the use of digital tools or tangible materials to enhance, acquire, and internalize this knowledge. For those with high spatial ability, the focus should not be on spatial skill training but rather on elucidating semantic spatial knowledge to help them effectively use spatial skills within the constraints of scientific principles or rules. The perspectives and interpretations presented in this study are expected to provide valuable directions for further exploration in future research.

Study Limitations

Three limitations of the study are as follows. First, other important aspects affect learning performance. This study focused only on the cognitive level, which refers to the quality of inference in conceptual understanding and the application of knowledge structures stored in long-term memory for transfer performance. It did not discuss affective factors (such as motivation, attitudes, and interest) and did not address teaching methods or learning processes (such as inquiry and collaborative learning). Second, the students in this study were at the 'initiate' level of the proficiency scale. Further discussion is needed for other proficiency levels, and longitudinal studies are needed to clarify the strength of the influences of general and domain-specific spatial abilities on the learning processes. Finally, although the results of this study were significant, a larger sample size is needed to replicate these findings.

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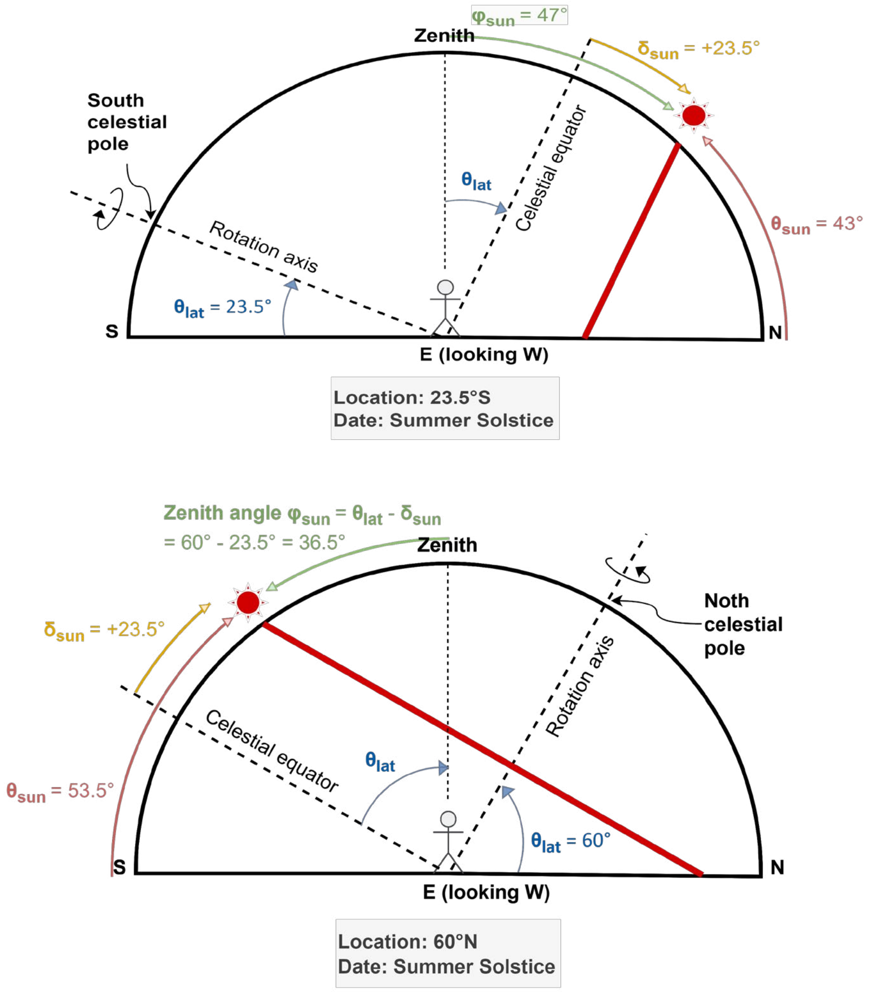
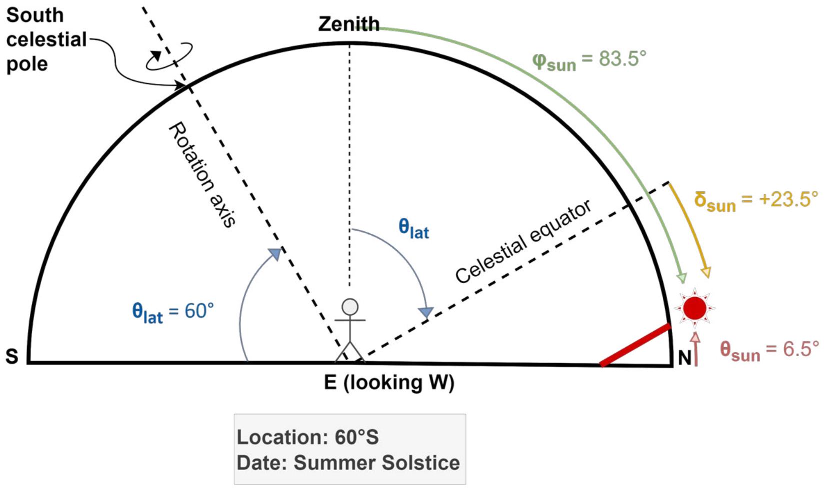
Appendix

Apparent Paths of the Sun at the Summer Solstice at 23.5°S, 60°N, and 60°S





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Yi-Chun Chen PhD, Assistant Professor, Teacher Education Center, & Institute of Education,
National Taiwan Ocean University, No.2, Beining Rd, Zhongzheng Dist,
Keelung City 202301, Taiwan.
E-mail: chyichun@mail.ntou.edu.tw
ORCID: https://orcid.org/0000-0002-7639-2392