Develop Three-dimensional Modeling and Printing Course to Improve Chinese Undergraduates' Spatial Ability

Weizhi Yang

A Thesis Submitted in Partial Fulfillment of Requirements for
degree of Doctor of Philosophy in Curriculum and Instruction

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ABSTRACT

Spatial ability has likely been a part of human cognition since early Homo sapiens. Spatial ability is important for various aspects of life and cognitive functioning. The structure of human intellect can be conceptualized as consisting of three broad but correlated domains: verbal ability, numerical ability, and spatial ability. Spatial ability plays a crucial role in creative design and scientific research.

Three-dimensional modeling and 3D printing have found widespread application in the field of education and have achieved significant accomplishments. They have opened up new possibilities in education, helping students develop spatial ability, creativity, and problem-solving skills. Emerging technologies and tools like three-dimensional modeling and 3D printing play a significant role in improving students' spatial ability.

However, there are still some shortcomings and challenges in research related to the application of three-dimensional modeling and 3D printing in enhancing spatial ability. These challenges related to defining and measuring spatial abilities, addressing diversity and cultural differences, managing the application of emerging technologies, and integrating these technologies into educational content effectively. Addressing these challenges will be essential for the successful implementation of such approaches in education.

The main purpose of this study is to introduce a 3D modeling and printing course to enhance the spatial ability of Chinese university students. With this research purpose in mind, a series of research questions are proposed, and research will be conducted around these questions. The research content will include: discussing the importance and necessity of improving spatial ability among university students, as well as the importance and necessity of offering a three-dimensional modeling and 3D printing course to enhance university students' spatial ability; the development of a three-dimensional modeling and 3D printing course curriculum; the implementation and monitoring of the course; and the evaluation of the course (including the

measurement of spatial ability).

Through the collection and organization of literature and data on spatial abilities, 3D modeling and printing, and related theories (such as spatial cognitive theory, multimodal theory, cognitive development theory), the importance and necessity of improving the spatial abilities of college students are analyzed and demonstrated, as well as the importance and necessity of applying the 3D modeling and printing course to enhance these abilities. A corresponding conceptual framework is proposed to guide the next steps of curriculum development, implementation, and evaluation, ensuring the applicability and effectiveness of the course. A comprehensive curriculum system for 3D modeling and printing is constructed, and quasi-experimental research is conducted through course implementation and evaluation.

The research results show that the 3D modeling and printing course indeed effectively enhances the spatial abilities of college students, and the improvement effects may vary among students of different majors, genders, and levels of spatial ability. Based on the improvement effects of students' spatial abilities and the evaluation and teaching feedback of the course, the applicability and effectiveness of the 3D modeling and printing course are proven.

In summary, the application of three-dimensional modeling and 3D printing technology to enhance the spatial ability of college students holds significant theoretical value and offers broad practical prospects. It plays a crucial role in promoting students' comprehensive development and improving their competitiveness. This will provide more opportunities in the field of education to meet the evolving demands of technology and careers, nurturing a new generation of university graduates with excellent spatial abilities who will make positive contributions to future scientific research and innovation.

Keyword : Spatial ability, Three-dimensional modeling, 3D printing, Curriculum development, Spatial cognition, Multimodal theory, Cognitive development

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CHAPTER I

INTRODUCTION

1.1 Background

1.1.1 Spatial Ability

Spatial ability can be defined in several ways depending on the context, such as: spatial intelligence, spatial aptitude, spatial skills, spatial awareness, spatial cognition, spatial perception, spatial problem-solving, spatial memory. The definition of spatial ability can vary in different fields and research contexts, but it typically involves the capacity to understand and process information related to space, location, and direction, as well as the ability to apply this information within specific domains. In the field of education, spatial ability is often defined as a student's ability to understand and process information related to space. This can include the ability to interpret geographical maps, comprehend geometric concepts, perform scientific experiments, or engage in engineering design, among other skills.

Spatial ability has likely been a part of human cognition since early Homo sapiens. Spatial ability is important for various aspects of life and cognitive functioning. The structure of human intellect can be conceptualized as consisting of three broad but correlated domains: verbal ability, numerical ability, and spatial ability (Wai et al., 2009). From the perspective of multiple intelligences theory, an individual possesses various intelligences, and each person's unique combination of these intelligences exhibits distinctive learning styles in their daily lives. Gardner[1], in his book "Frames of Mind"(Gardner, 1983), elaborates that a person has eight different intelligences, one of which is visual-spatial intelligence, which pertains to the ability to accurately perceive and express visual spatial information.

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[1] Howard Gardner (1943~), world renowned developmental and cognitive psychologist, founder of the theory of Multiple Intelligences, be acclaimed as the "Copernicus of the education field" and the "chief scientist driving educational reform in the United States".

Spatial ability plays a crucial role in creative design and scientific research(Carson & Campbell, 2007; Council et al., 2009; Honey & Kanter, 2013; Martinez & Stager, 2019). Just as Tesla[2] described in his autobiography(Tesla, 2013), he demonstrated powerful spatial ability when designing and improving engines. Einstein[3] also mentioned that he used visual spatial imagery, rather than verbal descriptions, in his thought processes when developing the Theory of Relativity(Newcombe, 2010). Watson and Crick[4]'s discovery of the double helix structure of DNA was also facilitated by the use of visual representations(Miller, 2013). Other examples include Kekulé[5] proposing the structure of the benzene ring and Feynman[6] developing quantum field theory(Shepard, 1978). These instances all emphasize the critical role of spatial ability in creative work and research.

With the development of the times and advances in technology (such as research in psychology and neuroscience), research on spatial ability has made significant progress. Spatial ability is important for academic, professional, and personal development. It enhances problem-solving, creativity, and adaptability in a wide range of contexts. Developing and honing spatial ability can have a positive impact on an individual's ability to navigate the world and excel in various pursuits. In education, there has been a growing recognition of the importance of spatial ability in science, technology, engineering, and mathematics (STEM) fields. Spatial ability tests are used to identify and develop spatial skills in students pursuing STEM careers.

There isn't a specific U.S. government report or policy that focuses solely on spatial ability. However, spatial ability and STEM (Science, Technology, Engineering,

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[2] Nikola Tesla (1856–1943) was a Serbian-American inventor, electrical engineer, mechanical engineer, and futurist who made significant contributions to the development of modern electrical systems and technologies. He is widely regarded as one of the greatest inventors and visionaries in history.

[3] Albert Einstein (1879–1955) was a German-born theoretical physicist who is widely regarded as one of the most influential scientists of all time.

[4] James Watson (1928~) and Francis Crick (1916–2004) were two prominent scientists who made one of the most significant scientific discoveries of the 20th century: the structure of DNA (deoxyribonucleic acid).

[5] August Kekulé (1829–1896) was a German chemist who made significant contributions to the field of organic chemistry. He is best known for his work on the structure of benzene and the development of structural formulas for organic compounds.

[6] Richard Feynman (1918–1988) was an American theoretical physicist known for his exceptional contributions to various fields of physics and his unique approach to teaching and explaining complex scientific concepts.

and Mathematics) education are often addressed in broader education and workforce development policies and reports. Spatial ability is an important component of STEM education, particularly in fields like engineering, mathematics, and geospatial sciences. STEM Education Initiatives: The U.S. government has been actively promoting STEM education to prepare the future workforce for science and technology-related fields. While these initiatives may not explicitly mention spatial ability, they often emphasize critical thinking, problem-solving skills, and the development of a strong foundation in mathematics and science, which are closely related to spatial reasoning. National Science Foundation (NSF): The NSF is a federal agency that supports research and education in various STEM fields. They have programs and initiatives aimed at improving STEM education, which indirectly contributes to the development of spatial ability in students. National Assessment of Educational Progress (NAEP): The NAEP is often used to assess the progress of U.S. students in various subjects, including mathematics and science. While not focused solely on spatial ability, these assessments provide insights into the overall performance of students in areas related to spatial reasoning. Career and Technical Education (CTE) Programs: Spatial skills are essential in many technical and vocational careers, and the U.S. government supports CTE programs that prepare students for these fields. Workforce Development: Workforce development initiatives often emphasize the importance of STEM skills, including spatial reasoning, to meet the demands of industries such as aerospace, engineering, and geospatial technology.

The Chinese government emphasizes the development of students' spatial ability in the field of education, particularly in STEM education. While there may not be specific government reports or policy documents dedicated to spatial ability, relevant policies and initiatives typically include the cultivation of students' ability in the field of space. STEM Education Policy: The Chinese government has consistently emphasized STEM education, encouraging students to develop skills in STEM, which often encompass space science and technology. STEM education policy documents may include curriculum standards, teaching methods, and resource allocation. National Education Reform and Development Plans: The Chinese government has issued multiple five-year plans and education reform documents, which typically include policy guidance on STEM education and the development of science and technology. Higher Education Institutions and Research Organizations: Chinese universities and research institutions often formulate their own education policies and plans to nurture students' ability in the field of space science and technology.

1.1.2 Three-Dimensional Modeling and Printing

Three-Dimensional Modeling (3D Modeling) is the process of creating a three-dimensional representation of an object or scene using specialized software or techniques. It is a digital method, typically based on 3D Computer-Aided Design (3D CAD) software, to design, simulate, and visualize the three-dimensional shape and appearance of objects. Three-dimensional modeling is widely used in various fields, including computer graphics, animation production, engineering design, architectural planning, medical imaging, game development, and virtual reality, among others.

Three-Dimensional Printing (3D Printing) is a manufacturing technology that involves the gradual construction of three-dimensional objects by layering or depositing materials. This technology has found widespread applications across various industries, including manufacturing, healthcare, aerospace, automotive, art, and design, among others. It offers new possibilities for prototyping, custom part production, rapid manufacturing, and innovative design. Typically, 3D printing also includes the three-dimensional modeling process.

3D printing technology, as one of the primary methods for realizing physical objects from 3D models, is also a major avenue for integrating 3D modeling into education. It has been referred to as "the idea of the 19th century, the technology of the 20th century, and the market of the 21st century." An article in The Economist magazine from the UK suggests that 3D printing technology will be one of the technologies driving the realization of the third industrial revolution. As one of the popular technologies in recent years, 3D printing has gradually entered various levels of schools. It has been integrated into the education sector through means such as 3D printing courses, maker competitions, the integration of 3D printing with various subjects, and summer camps. In 2013, the "NMC Horizon Report: 2013 Higher Education" provided a detailed introduction to 3D printing in its long-term technological applications. It included 3D printing education applications in the "to be adopted" list of new technologies and predicted that 3D printing technology would be applied and developed within 4-5 years(Johnson et al., 2013) .

In the mid-term trend section of the 2014 " NMC Horizon Report: 2014 Higher Education ", it was suggested that 3D printing would be adopted as an educational technology within 2-3 years(Johnson et al., 2014). The " NMC Horizon Report" in 2015 and 2016 also mentioned 3D printing technology in its mid-term technological trends(L. Johnson et al., 2016; Nmc, 2015). In 2015, China released the "National Additive Manufacturing Industry Development Promotion Plan (2015-2016)," which elevated the development of the 3D printing industry to the national strategic level and formulated a comprehensive plan for the development of the 3D industry. This plan proposed to accelerate the application of 3D printing technology in education and encouraged eligible schools to carry out teaching practices. In the same year, the State Council issued the "Guiding Opinions on Actively Promoting New Consumption to Accelerate the Cultivation of New Supply and New Driving Forces," which stated, "Promote the rapid development of segmented industries such as 3D printing, robotics, genetic engineering, and network security to explore new areas of consumption." In September 2017, the Ministry of Education issued the "Guidelines for Comprehensive Practical Activities in Primary and Secondary Schools," recommending that students in grades 7-9 learn 3D printing and encouraging schools to purchase 3D printers.

1.2 Research Status and Challenges

Three-dimensional modeling and 3D printing have had a significant impact not only on the manufacturing and technology industries but also on their countless applications in the field of education. As 3D printing technology continues to mature, many countries have formulated policies related to 3D printing education and allocated substantial funding for it. In European and American countries, 3D printing technology has been widely adopted in the field of education, becoming a powerful tool to promote STEM (Science, Technology, Engineering, and Mathematics) education. Many classrooms in the United States have introduced 3D printers as essential teaching tools and methods. In China, inspired by Western countries like the United States, research on the use of 3D printing in education has grown significantly. Many primary and secondary schools, especially those in major cities like Beijing, Shanghai, and Guangzhou, have equipped themselves with 3D printers, establishing innovation labs and incorporating 3D printing in various forms, such as clubs and competitions, into their classrooms.

Three-dimensional modeling and 3D printing have found widespread application in the field of education and have achieved significant accomplishments. They have opened up new possibilities in education, helping students develop spatial ability, creativity, and problem-solving skills. Research on enhancing spatial ability through three-dimensional modeling and 3D printing can be divided into two categories: technology-based approaches and instructional methods for improving spatial ability. The first category explores whether 3D printing technology or 3D modeling software can enhance students' spatial ability, while the second category investigates whether certain teaching methods based on three-dimensional modeling and 3D printing can improve students' spatial ability. The application of emerging technologies to the enhancement of spatial ability offers new opportunities in research and education. Emerging technologies and tools like three-dimensional modeling and 3D printing play a significant role in improving students' spatial ability. However, there are still some shortcomings and challenges in research related to the application of three-dimensional modeling and 3D printing in enhancing spatial ability:

(1) Complexity of Definition and Measurement: Spatial ability is multidimensional, and they span across various disciplines. Defining and measuring these abilities accurately is a challenge since there are no universally accepted standards and measurement tools. Therefore, researchers and educators may choose different definitions and measurement tools based on their research objectives and backgrounds, making it crucial to select appropriate tools and measurement methods for assessing spatial ability.

(2) Diversity and Cultural Differences: Students' spatial ability can be influenced by cultural, social, and educational backgrounds. Individuals from different cultural backgrounds may exhibit varying levels of spatial ability. Hence, research needs to consider differences among students from different cultures and backgrounds, which adds complexity to the research.

(3) Application of Emerging Technologies: While emerging technologies like three-dimensional modeling and 3D printing hold potential in spatial ability research, their application also faces challenges related to technology, resources, costs, and sustainability. Additionally, more empirical and comparative studies are needed to evaluate the effectiveness of emerging technologies and tools compared to traditional methods in enhancing spatial ability.

(4) Integration into Educational Content: Effectively integrating the technology and tools of three-dimensional modeling and 3D printing into educational practices to enhance students' spatial ability is a complex task that requires attention to multiple research directions. Key among them is the development of effective curriculum design and teaching strategies.

The school selected in this study is Jiaying University, which is a general comprehensive undergraduate university. The university is located in Guangdong Province, one of the most economically developed provinces in China. Like other colleges and universities, the cultivation of undergraduates' spatial ability has not been highlighted. 3D modeling and printing, as one of the emerging technologies, has not yet formed a universal or independent professional existence in universities, but in some majors or some courses, the integration of 3D modeling and 3D printing part of the content. In universities, there are no cases of integrating 3D modeling and 3D printing as independent courses for students of different majors, with the aim of cultivating spatial ability as the orientation.

1.3 Research Purposes, Questions, and Contents

The main theme of this study is to introduce a 3D modeling and printing course to enhance the spatial ability of Chinese university students.

Based on this research theme, the following research questions are proposed:

Question 1: Why should we enhance the spatial ability of university students?

Question 2: How can we improve the spatial ability of university students?

Question 3: Why should we develop 3D Modeling and Printing course for university students?

Question 4: How can we implement 3D Modeling and Printing course for university students?

Question 5: How can we measure university students' spatial ability and their changes?

Question 6: Whether the 3D Modeling and Printing course has improved the spatial ability of university students?

Question 7: What are the specific changes in the spatial ability of university students?

Therefore, the purpose of this research can be divided into the following four points: ① To demonstrate and analyze the importance, necessity and feasibility of 3D modeling and 3D printing courses to improve the spatial ability of college students. ② Design and develop a set of feasible 3D modeling and printing courses. ③ To evaluate the spatial ability level of Chinese college students, and explore and analyze the factors that affect the spatial ability level of college students. ④ This paper analyzes the influence of curriculum implementation on students' spatial ability by measuring their spatial ability before and after curriculum implementation. The research purposes and questions are shown in Figure 1. Based on these research questions, a series of related analyses and studies were conducted:

(1) A systematic review of relevant research findings on spatial ability, with analytical arguments addressing three questions: Why should we enhance the spatial ability of university students? How can we improve the spatial ability of university students? How can we measure university spatial ability and their changes?

(2) Citation and analysis of relevant theories (including spatial cognition theory, multimodal theory, cognitive development theory), combined with the content analysis from the previous section and the characteristics of 3D modeling and 3D printing technology/tools, addressing the question: Why should we offer a 3D modeling and printing course? How can we implement a 3D modeling and printing course?

(3) Empirical research: In accordance with the guidance of spatial ability research findings and relevant theories, the implementation of 3D modeling and printing courses was carried out, addressing question 6: Whether the 3D modeling and printing course has improved the spatial ability of university students? After the course implementation, specific analysis and arguments regarding changes in

university students' spatial ability were provided, along with constructive feedback and teaching recommendations.

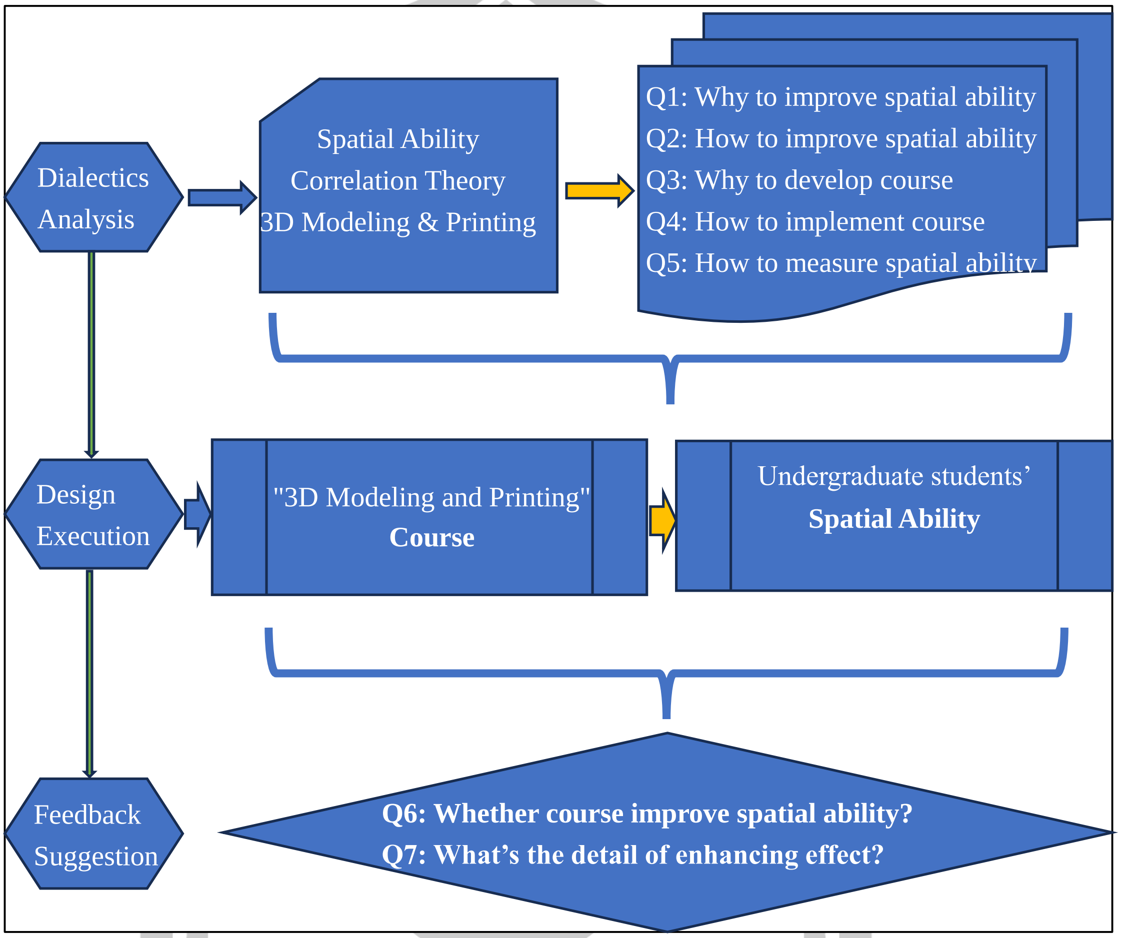


Figure 1 Research purposes and questions

1.4 Significance of the Research

This study addresses the shortcomings and challenges in the research aimed at enhancing the spatial ability of college students through the application of emerging technologies. It conducts a series of theoretical and empirical research efforts. The primary objectives of this research are to improve college students' spatial ability by offering a course on three-dimensional modeling and printing. The research has both theoretical and practical significance.

Theoretical Significance:

(1) Filling Theoretical Gaps: Currently, the field of spatial ability research faces theoretical deficiencies and disputes. Through this study, we can comprehensively analyze and explore the mechanisms and effects of using three-dimensional modeling and 3D printing technology to enhance spatial ability, thereby filling theoretical gaps in existing research.

(2) In-Depth Analysis of Influencing Factors: This research conducts an in-depth analysis of various factors affecting spatial ability, including age, gender, and academic discipline. This analysis will contribute to a better understanding of the process of spatial ability development, providing robust theoretical support for future related research.

(3) Innovation in Educational Methods: By introducing three-dimensional modeling and 3D printing technology, the research offers an innovative educational approach, exploring how technology can be used to enhance students' spatial abilities. This has positive implications for the theoretical development of the education field.

Practical Significance:

(1) Educational Improvement: Applying three-dimensional modeling and 3D printing technology in higher education can enhance teaching quality and students' learning experiences. Students will improve their spatial abilities through practical hands-on activities and creative thinking, better preparing them for the demands of various academic disciplines and professions.

(2) Enhancing Employability: Modern job markets increasingly demand spatial ability, especially in fields like design, engineering, and architecture. By cultivating students' spatial abilities early on, this research can enhance their competitiveness in the job market and provide a strong foundation for their future careers.

(3) Expanding Technological Applications: Three-dimensional modeling and 3D printing technologies have wide-ranging applications in fields such as healthcare,

manufacturing, and the arts. Nurturing students' spatial abilities opens up possibilities for them to apply these technologies in their future work, promoting technological innovation and societal progress.

(4) Reference for Educational Reform: This research serves as a case study for educational reform, demonstrating how emerging technologies can be integrated into educational curriculum development. This has a positive demonstration effect on driving reforms and development in the education field.

In summary, the application of three-dimensional modeling and 3D printing technology to enhance the spatial ability of college students holds significant theoretical value and offers broad practical prospects. It plays a crucial role in promoting students' comprehensive development and improving their competitiveness.

1.5 Definition and Scope of the Research

(1) SPATIAL ABILITY

Spatial ability is a term in cognitive psychology, which is considered an important part of human intelligence structure and a relatively independent cognitive ability in higher cognitive activities. From the thesaurus of ERIC (an online library of educational research and information, sponsored by the Institute of Education Sciences of the U.S. Department of Education), spatial ability is the ability to perceive or solve problems associated with relationships between objects or figures, including position, direction, size, form, and distance (Note: Prior to mid-1980, this concept was indexed under "Space Orientation" and "Spatial Relationship" -- do not confuse with "Personal Space"). Further, spatial ability refers to an individual's capacity to perceive, understand, manipulate, and reason about objects, shapes, and the spatial relationships between them. It encompasses the mental skills and aptitudes that enable a person to visualize objects and their arrangements in three-dimensional space, solve spatial problems, and navigate within their environment effectively. In different times and different studies, spatial ability has been called different things, such as spatial abilities, spatial skill(s), spatial capability, spatial Intelligence, spatial reasoning, spatial awareness, spatial memory, spatial thinking, and so on. Although there has not been a clear definition of spatial ability until now, the term “spatial ability” has been more widely used in related studies. Spatial ability is often measured through tasks like mental rotation, spatial visualization, and spatial reasoning, and it plays a significant role in various fields, including mathematics, science, engineering, architecture, and the arts. Individuals with strong spatial ability tend to excel in tasks that involve visualizing and manipulating spatial information.

(2) SPATIAL VISUALIZATION ABILITY

Spatial visualization (VZ) is a cognitive skill that involves the ability to mentally manipulate and transform visual images or objects in three-dimensional space. It enables individuals to visualize and understand the spatial relationships between objects, their positions, orientations, and how they change when manipulated. In essence, spatial visualization is the mental ability to see, understand, and work with objects and spatial relationships in one's mind, without the need for physical manipulation. Although the definition and classification of spatial ability are not very clear, and the various subfactors of spatial ability are interrelated, researchers generally agree that spatial visualization ability is one of the main components of spatial ability. Due to the use of specific spatial ability testing tools in this study, the empirical research analysis in this paper is mainly aimed at the spatial visualization ability of students.

(3) THREE-DIMENSIONAL MODELING

Three-dimensional modeling, often referred to as 3D modeling, is the process of creating a three-dimensional representation of an object, scene, or environment using specialized software or techniques. Three-dimensional computer-aided design (3D CAD), is technology for design and technical documentation, which replaces manual drafting with an automated process. Used by architects, engineers, and other professionals, 3D CAD software precisely represents and visualizes objects using a collection of points in three dimensions on the computer. These models are used in various fields and applications, including computer graphics, animation, architecture, engineering, video games, virtual reality, product design, and more. Here are the key aspects and steps involved in three-dimensional modeling: Object or Scene Representation; Geometry Creation; Mesh Creation; Texture Mapping; UV Mapping; Lighting and Shading; Rigging and Animation; Rendering; Optimization; Export and Integration. Three-dimensional modeling is a versatile and powerful tool that plays a crucial role in many industries. It allows for the creation of realistic and interactive 3D environments, objects, and characters, enhancing visual communication and problem-solving in a wide range of fields.

(4) THREE-DIMENSIONAL PRINTING

"Three-dimensional printing" is essentially another way of referring to "3D printing" or "additive manufacturing." It's the process of creating three-dimensional objects by adding material layer by layer, based on a digital model. The term emphasizes the use of three dimensions (length, width, and height) to build physical objects, making it a precise synonym for 3D printing. Here's a quick summary of how three-dimensional printing works: Slicing; Material Selection; Loading Material; Calibration; Printing; Cooling and Solidifying; Support Structures (if needed); Post-Processing; Quality Control; Final Product. In much of the literature, modeling is included in 3D printing. However, 3D models for 3D printing can be obtained in other ways, such as 3D scanning, downloading from the Internet and so on. For the sake of distinction, 3D printing here does not include design modeling. 3D printing has a wide range of applications across various industries, including manufacturing, healthcare, aerospace, education, automotive, art, and more, as outlined in the previous response. It offers benefits such as rapid prototyping, customization, and the ability to create complex geometries that traditional manufacturing methods may struggle with. There are several different forms or techniques of 3D printing, each with its own unique method of creating three-dimensional objects. Fused deposition modeling (FDM) was used in this study. Because of the cost considerations, FDM is one of the most widely used 3D printing techniques (especially in the education industry). It works by melting a thermoplastic filament and extruding it through a nozzle onto a build platform layer by layer. The material solidifies as it cools, creating the object.

(5) THREE-DIMENSIONAL MODELING AND PRINTING COURSE

Three-dimensional modeling and printing course (3DMP) is a general elective course for college students developed and designed in this research. It is a course developed based on theories of spatial cognition, multimodality, and cognitive development, using a hybrid curriculum development model. Its main purpose is to enhance the spatial ability of college students, and its primary content involves the integration and application of emerging technologies, including the technology, software, and equipment related to 3D modeling and printing.

CHAPTER II

REVIEW AND FRAMEWORK DESIGN

2.1 Spatial Ability

2.1.1 Development History of Spatial Ability

The concept of spatial ability and its development can be traced through various historical periods and fields of study. An overview of the historical development of spatial ability is shown in Table 1 (1993; Lohman, 1979; Newcombe & Shipley, 2014; Wai et al., 2009). Spatial ability has likely been a part of human cognition since early Homo sapiens. Primitive humans needed spatial skills for navigation, hunting, and tool-making. The creation of cave art and early architectural structures also suggests the presence of spatial thinking. Greek mathematicians like Euclid and Pythagoras made significant contributions to the development of geometry, which is closely tied to spatial thinking. Euclid's "Elements" laid the foundation for geometric principles that are still taught today. During the Renaissance, artists and architects developed linear perspective techniques to accurately represent three-dimensional space on a two-dimensional surface. Artists like Leonardo da Vinci and Filippo Brunelleschi made important advancements in this area. The Industrial Revolution brought advancements in engineering and manufacturing, requiring spatial skills for designing machines and structures. Civil engineers like Isambard Kingdom Brunel and Gustave Eiffel contributed to the field. Psychologists began studying spatial ability as a distinct cognitive skill. Francis Galton's work in the late 19th century and the subsequent development of intelligence tests (e.g., Stanford-Binet IQ test) included spatial reasoning as a component of intelligence. During World War II, aviation and military applications drove research into spatial ability, as pilots needed strong spatial skills for navigation and combat. The development of spatial aptitude tests, such as the Purdue Spatial Visualization Test, is a result of this era. The space race between the United States and the Soviet Union in the mid-20th century emphasized the importance of spatial thinking in fields like astronautics and rocket science. The development of computer graphics and video games in the late 20th century further advanced spatial thinking as players navigated and interacted with virtual three-dimensional environments. In education, there has been a growing recognition of the importance of spatial ability in science, technology, engineering, and mathematics (STEM) fields. Spatial ability tests are used to identify and develop spatial skills in students pursuing STEM careers. Advances in neuroscience and brain imaging have allowed researchers to study the neural underpinnings of spatial ability, shedding light on how the brain processes spatial information.

Table 1 Historical Overview of the Development of Spatial Ability

Stage	**Time Period**	**Key Developments and Events**
Early Human History	Prehistoric to Ancient Times	Navigation, hunting, tool-making
Ancient Greece	15th-16th Century BC	Euclidean geometry foundations
Renaissance	15th-16th Century	Linear perspective in art
Industrial Revolution	18th-19th Century	Spatial skills for engineering
Psychology Research	Late 19th-20th Century	Study of spatial ability as a cognitive skill
World War II	20th Century	Spatial skills for aviation
Space Exploration	20th Century	Emphasis on spatial thinking in astronautics
Computer Graphics	Late 20th Century	Development of 3D graphics and gaming
Educational Research	Late 20th-21st Century	Recognition in STEM education
Neuroscience	21st Century	Study of neural basis of spatial ability

The historical development of spatial ability has been influenced by a wide range of factors, including technological advancements, educational needs, and shifts in cognitive psychology and neuroscience research. In essence, research into spatial ability is multidisciplinary and has broad applications, influencing fields ranging from education and technology to design and neuroscience. Understanding its historical development provides context for its ongoing significance in contemporary research. By sorting out the historical development of spatial ability, we can better understand the importance of spatial ability to human development and explore the possible direction of spatial ability development research.

2.1.2 Definition of Spatial Ability

Spatial ability is considered to be an important part of human intelligence structure(Galton, 2020). Like speech cognition, it is a relatively independent cognitive ability in human higher cognitive activities(Mohler, 2008). Galton's research on visual representation in the 1880s is considered to be the origin of modern spatial competence research. In the past hundred years, a lot of research has been devoted to the definition of space ability and the analysis of space ability structure, but there is still no consensus on the definition of space ability. Some scholars have defined the concept of spatial ability from different disciplines or research perspectives. Table 2 shows the definition or relevant views of some famous scholars on spatial ability

Table 2 Definition or Relevant Views on Spatial Ability

Researchers	**Definition of Spatial Ability or Related Concepts**
Alfred Binet (1911)	As one of the pioneers of intelligence testing, Binet considered spatial ability to be part of intelligence, including understanding and manipulating three-dimensional relationships of objects.
Roger Shepard (1971)	Shepard is one of the leading authorities on spatial cognition, focusing on the human capacity for spatial imagination and rotation. Spatial ability, he argues, involves "the ability to rotate and manipulate visual objects in your mind to get different angles."
David Lohman(1979)	Spatial ability is the ability to understand and remember the spatial relations among objects or space as separate from objects.
Howard Gardner (1983)	Gardner's theory of multiple intelligences includes "spatial intelligence," which refers to a person's ability to perceive and understand space, such as navigation, graphics, and spatial schematics.
John M. Carroll (2003)	Carroll, an expert in human-computer interaction and computer science, explores the use of spatial capability in user interface design and virtual reality.
David Uttal (2013)	Uttal is a cognitive psychologist whose research deals with the role of spatial ability in education and cognitive development, particularly its application in science and mathematics education.

These scholars' definitions and concepts cover different aspects of spatial competence, including understanding, remembering, imagining, and thinking about spatial relationships. These definitions are important for cognitive psychology, educational psychology, and related research fields, contributing to a deeper understanding of human cognitive and thought processes, as well as the role of spatial ability in a variety of tasks and domains. The work of these researchers has laid the foundation for modern studies of spatial capability, and their research has led to a better understanding of how humans perceive, understand, and manipulate spatial information. The study of spatial ability has a broad interdisciplinary nature, and modern spatial ability research has been extended to various fields, including psychology, education, neuroscience, computer science and engineering, and it has important significance in cognitive science and practical applications. The following is the definition of spatial ability from the perspectives of cognition, psychology and education, which is also the theoretical basis of this research on spatial ability.

Cognitive Definition: Spatial ability refers to an individual's capacity to understand, interpret, and manipulate spatial information in their environment. It encompasses skills such as mental rotation, spatial visualization, and spatial reasoning.

Psychological Definition: In psychology, spatial ability is often described as a cognitive skill related to the mental representation and manipulation of objects and their spatial relationships. It includes the ability to mentally rotate objects, visualize spatial layouts, and solve spatial problems.

Educational Definition: In education, spatial ability is seen as a critical skill for success in STEM fields. It involves the ability to grasp and work with spatial concepts and representations.

2.1.3 Factors and Classification of Spatial Ability

Spatial ability, as a basic cognitive ability, includes a series of basic cognitive processing processes, such as recognition, encoding, storage, representation, decomposition/combination and abstraction/generalization of visual objects or images in the mind. On the basis of the definition of spatial ability, many researchers believe that spatial ability is composed of multiple elements rather than a single ability. Subsequent studies have found the diversity of spatial cognitive processing ability and have attempted to decompose spatial ability into a series of meaningful spatial factors

(Guilford, 1956; Heyden et al., 2017; Kosslyn, Margolis, et al., 1990; Lehmann et al., 2014; Linn & Petersen, 1985; Wang & Carr, 2014). Lohman(1979) believes that if various specific spatial factors can be clearly classified, spatial ability can be better measured. However, after a series of related studies, it is difficult to describe it clearly. The main reason is that these studies decompose the spatial cognitive processing into different spatial factors, adopt different factor analysis methods, and do not reach a consensus on the quantity, composition and interpretation of spatial factors.

D' Oliveira (2004) pointed out four main aspects of controversy regarding research into spatial ability: (a) definitions of spatial ability and each spatial factor varied across researchers; (b) different numbers of spatial factors were identified; (c) some spatial factors had identical names but their definitions were different and vice versa; and (d) a variety of spatial tests used to measure each spatial factor existed and resulted in confusion because of a mismatch between the tests' name and content. Table 3 shows typical spatial factors' definitions by researchers frequently cited in the literature. As D' Oliveira argued, their definitions and categorizations are subtly different and blend into one another.

Table 3 Summary of Spatial Ability Factors

Study	**Subcategories Identified**
French (1951)	Space; Spatial Orientation
McGee (1979)	Spatial Orientation; Spatial Visualization
Lohman (1979)	Spatial Relations; Spatial Orientation; Spatial Visualization.
Linn & Petersen (1985)	Spatial Perception; Mental Rotation; Spatial Visualization
Kritchevsky (1988)	Spatial Perception; Spatial Memory; Spatial Attention; Spatial Mental Operation; Spatial Construction
Carroll (1993)	Spatial Visualization; Spatial Relations; Visual Memory; Perceptual Speed; Closure Speed; Closure Flexibility
Maier (1999)	Spatial Perception; Mental Rotation; Spatial Relations; Spatial Orientation; Spatial Visualization
Uttal et al.(2013)	Intrinsic; Extrinsic; Static; Dynamic

According to the above definition and component factors of spatial ability, it can be found that spatial ability mainly involves three relationships, namely, the relationship between objects, the relationship between objects and objects, and the relationship between objects and observers. There are differences on how to decompose and describe spatial ability, but a large number of studies agree on two main spatial factors: spatial orientation ability and spatial imagination.

Based on the research of McGee (1979) and based on the perspective of mental processes, Tartre (1990) proposed a classification structure of spatial ability, as shown in Figure 2. This mental processing is considered to be used when performing specified tasks. Tartre believed that spatial ability contains two clear components: spatial visualization and spatial orientation. The spatial visualization component involves mentally moving objects, and the spatial orientation component involves the individual's ability to mentally move one's perspective while the object remains fixed in space. Tartre also pointed out that the spatial visualization component can be subdivided into mental rotation and mental distortion. Mental rotation means that an object is completely rotated and deformed in space; while mental deformation means that only part of the object is deformed in some way. Many researchers classify the mental rotation of two-dimensional and three-dimensional stimuli as spatial orientation or spatial relationship, while Tartre regards mental rotation as a component of spatial vision, which is due to the fact that the stimulus is moved mentally.

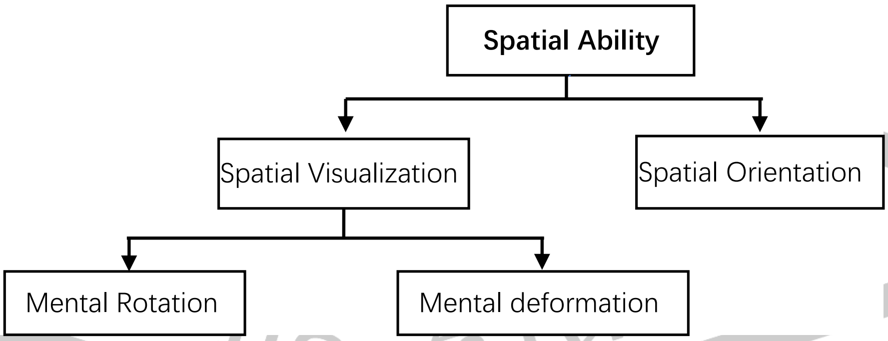


Figure 2 Tartre’s spatial capability classification structure

Although spatial visualization ability is considered an effective psychological construction ability, there is still no consensus on its definition due to different levels of discussion. Ekstrom et al. (1976) pointed out that spatial visualization is the ability to mentally manipulate or transform spatial graphics; kahle et al.(1983) believed that spatial visualization is the ability to manipulate objects or patterns in imagination; Salthouse et al.(1990) advocated that, Spatial visualization is the mental manipulation of spatial information to determine how a specified spatial figure will look if it is rotated, folded, shifted, or deformed. Smith(2001) defines spatial visualization as a method involving the shape and structure of objects, mainly using mental imagery, which can clearly retain the topological and geometric relationships of the problem, and the ability to solve multi-stage problems. In addition, it may also involve additional Logical, linguistic and symbolic reasoning.

2.1.4 Measurement of Spatial Ability

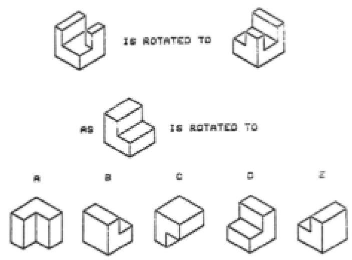
The development of spatial ability measurement has been paralleled by the development of spatial ability research. The measurement of spatial ability is to assess an individual's ability in spatial cognition and processing through a series of psychometric tools and tasks. These measurement tools are commonly used by psychologists, cognitive scientists, and educational researchers to understand an individual's level of spatial ability. Some common spatial ability measurement methods and tools include: spatial ability tests, map reading tasks, three-dimensional puzzle tasks, plane geometry tasks, visual-spatial working memory tasks, task questionnaires and self-reports, neuroimaging studies, etc. Tests of spatial ability are tools used to assess an individual's ability to process spatial information, spatial perception, and spatial reasoning. Some common spatial ability tests include: Mental Rotations Test（MRT）; Vandenberg MRT; Raven's Progressive Matrices; Block Design Test; Water Level Task; Virtual Reality Tests; Map Reading Tests; Plane Geometry Tests. These measurement methods or testing tools can be used individually or in combination to assess an individual's spatial ability level according to the purpose of the study and the needs of the researcher.

Over the past hundred years, educators and researchers have developed a variety of measurement and testing tools and methods to assess the spatial ability of specific individuals. These tools or methods have evolved from initially designed for experiments to standardized testing tools or methods. However, because not all of these tests measure the same spatial factors, and because many have been lost, abandoned, or restricted in their use during development, researchers still lack effective scales for studying the complex components of spatial ability(Zhang, 2014).

Visualization tests included more complex, multi-step components, and several correct answers(Wang, 2016). These test methods included the Heinrich Spatial Visualization Test (HSVT), Purdue Spatial Visualization Test (PSVT), Purdue Spatial Visualization Test-Visualization of Rotation (PSVT-R), Purdue Visualization of Rotations Test (ROT).(Harris, 2019) Abbreviated versions of these tests were also available (Muffato et al., 2017; Nagy-Kondor, 2016; Wang, 2016).

Guay(1976) originally developed the Purdue Spatial Visualization Test, consisting of three different subtests entitled “Developments,” “Rotations,” and “Views,” which contains a total of 36 items, 12 from each subtest. Each subtest of the PSVT also had an independent extended version of 30 items entitled the Purdue Spatial Visualization Tests: Visualization of Developments (PSVT:D), Visualization of Rotations (PSVT: R), and Visualization of Views (PSVT: V). Among the three extended versions of the PSVT, the PSVT:R is a 20 minute test for individuals aged 13 or older used to measure spatial visualization ability in 3-D mental rotation (Guay, 1980). The PSVT: R has 2 practice items followed by 30 test items which consist of 13 symmetrical and 17 asymmetrical figures of 3-D objects, which are drawn in a 2-D isometric format. All the figures contain shapes of cubes or cylinders with varied truncated slots. (see Figure 3 for an example) The items are ordered to be progressively more difficult, based on the rotated angles and axes (Guay, 1980).. In each item, respondents are shown a figure and its rotated figure for an example of rotation and asked to find another figure's match as rotated in the same way of the example. The five given choices are rotated in different directions and shown at different angles.

Purdue Spatial Visualization Tests: Visualization of Rotations (PSVT:R) (Guay, 1976)



Direction: Choose the object that has the same rotation as shown in the top line

Figure 3 An example of PSVT:R

Since its development by Guay(1976), the PSVT:R has been used primarily in the research of educational settings in the science, technology, engineering, and mathematics (STEM) disciplines. The PSVT:R has been one of the most popular tests in engineering education to measure students' spatial visualization ability of mental rotation (Contero et al., 2005; Field, 2007). This is because, compared to other popular spatial tests including the Mental Cutting Test (MCT), Mental Rotations Test (MRT), Revised Minnesota Paper Form Board Test (RMPFBT), and Differential Aptitude Tests: Spatial Relations (DAT:SR), for research in engineering education, the PSVT:R is unique in that 3-D objects in the test have inclined, oblique, and curved surfaces, which are more demanding to visualize than simple surfaces consisting of cubes as used in other tests (Yue, 2004).

Yoon(2011) noted that there could be several explanations for the prevalence of the PSVT:R in the STEM areas, especially in engineering. First, the PSVT:R data show strong reliability and validity evidence. Second, inference was made to the PSVT:R in credible resources, such as the Educational Testing Service Test Collection (Service, 2009) and An International Directory of Spatial Tests (Eliot, 1984). Third, the tasks in the PSVT:R consist of spatial problems closely aligned with the tasks routinely required to succeed in the engineering and technology disciplines(Yue, 2004). Fourth, the PSVT:R has the necessary complexity and difficulty of items to differentiate STEM students' degree of spatial ability (Black, 2005; Yue, 2006). Fifth, the PSVT: R is free to use and readily available. and difficulty of items to differentiate STEM students' degree of spatial ability(Black, 2005; Yue, 2006). Fifth, the PSVT: R is free to use and readily available.

Due to concerns about inconsistent usage of PSVT:R and the discovery of bugs in PSVT:R, Yoon(2011) and team members modified PSVT:R and formed the Revised PSVT:R. The Revised PSVT: R is the spatial ability testing tool used in this study.

2.1.5 Important of Spatial Ability

The structure of human intellect can be conceptualized as consisting of three broad but correlated domains: verbal ability, numerical ability, and spatial ability (Wai et al., 2009). Spatial ability is important for various aspects of life and cognitive functioning. Here are some key reasons why spatial ability is considered important:

Academic Achievement: Spatial ability plays a crucial role in academic subjects like mathematics, science, engineering, and architecture. It helps individuals understand and work with spatial relationships, which are often fundamental in these fields. Verbal and numerical ability are traditionally emphasized in the classroom context, as the phrase "the three Rs" (reading, writing, and arithmetic) suggests. However, research has increasingly demonstrated that spatial ability also plays an important role in academic achievement, especially in learning STEM (Buckley et al., 2018; Council et al., 2005; Lin & Suh, 2021; Newcombe, 2010). "Understanding the factors that impact learners with respect to their academic achievement is critical for enhancing educational provision……In light of the overwhelming evidence illustrating that spatial ability, commonly described as the ability to generate and manipulate abstract visual images, is positively associated with STEM educational performance and retention”(Buckley et al., 2022). This is attributed to the fact that learners need to mentally establish and manipulate visuospatial information using their spatial ability to understand the knowledge in STEM subjects. Therefore, learners with high spatial ability tend to exhibit better learning performance.

Occupational Proficiency: Many professions require spatial ability. For example, surgeons use it to perform precise operations, pilots rely on it for spatial awareness in the air, and construction workers use it for accurate building and layout. Spatial ability is positively correlated with students' academic performance (especially in STEM majors), which in turn affects students' employment choices. Various types of spatial ability tests are widely used for student admission and pre-employment screening. Researches show that students who are spatially gifted are more likely to pursue STEM careers(J. F. Johnson et al., 2016; Weber, 2020; Yoon & Mann, 2017).

Navigation: Spatial ability is essential for navigation and wayfinding. People with strong spatial skills tend to have better navigational ability, whether in urban settings, wilderness environments, or when using GPS systems. Navigation is a special kind of spatial thinking, which requires us to understand our location (where we are) and orientation (which direction we are facing) in relation to the surroundings. Spatial orientation and navigation may be problematic for some people even with maps or satellite navigation(Ishikawa, 2018; Liben et al., 2002).

Problem Solving: Spatial ability aids in problem-solving and critical thinking. It allows individuals to visualize complex scenarios and develop innovative solutions. This is especially valuable in engineering, design, and scientific research.

Technology and Gaming: Spatial ability is valuable in technology-related fields. Game developers, virtual reality designers, and programmers often need strong spatial skills to create immersive digital experiences.

Cognitive Development: Spatial ability is linked to cognitive development, especially in children. Engaging in spatial activities and games can enhance cognitive skills and lay the foundation for later academic success.

Everyday Life: Spatial ability is useful in everyday life tasks such as organizing space, arranging furniture, reading maps, and understanding diagrams and blueprints. Space is s fundamental component to our cognition and behavior, as it surrounds us and affords us opportunities to function adaptively(Ishikawa & Newcombe, 2021). Thinking in, about, and with space characterizes (or conditions) our everyday activities. Finding one's way in the environment (cognitive mapping), communicating information in graphs and diagrams (visualization), and using space to think about nonspatial phenomena (spatial metaphors or spatialization) are major examples of our everyday spatial thinking, to name but a few.

In summary, spatial ability is important for academic, professional, and personal development. It enhances problem-solving, creativity, and adaptability in a wide range of contexts. Developing and honing spatial ability can have a positive impact on an individual's ability to navigate the world and excel in various pursuits.

Spatial visualization is one of the important components of spatial ability, which has been widely concerned by researchers in the fields of engineering, mathematics, chemistry, art and design. As Devon et al. (1994) said, spatial visualization is a very important component in engineering as it is directly related to design and graphical communication. Rhoades (1981) also pointed out that this ability to create mental imagery of objects and be able to manipulate it mentally is of great significance for the learning of mathematics, geometry, physics, chemistry, etc., or for the performance of professional skills such as medicine, architecture, mechanics, engineering, and design. The study of Gobert(1999; 2000) shows that in architectural design performance, spatial visualization ability is correlated with the acquisition, understanding and development of three-dimensional representation of architectural graphic information. Moreover, spatial visualization ability and spatial orientation ability also have an impact on the extraction of high-level architectural knowledge. In the field of human-computer interaction, the difference in spatial visualization ability enables some users to query and retrieve information more effectively. This difference does not mean that users with low spatial visual ability cannot find information, but the query speed is slower. Therefore, spatial visualization ability is considered to be the vane of future career success for students engaged in these fields, and has good predictive validity for individual growth and future achievement.

2.1.6 Difference of Spatial Ability and Related Factors

There are differences in spatial ability among people, and there are also differences in spatial ability among individuals in different situations (such as at different ages). The difference of spatial ability in people or individuals is caused by many reasons, influenced by many factors, and is the result of the interaction of many factors. Exploring the factors and manifestations of differences in spatial ability can better understand the true level of a person's spatial ability, and further explore possible countermeasures and means to improve spatial ability, such as optimizing training and education methods.

Here, the factors that cause differences in spatial ability are divided into two categories: internal factors and external factors. The two types of factors separately or interacted to cause the difference in spatial ability, as shown in Figure 4. Internal factors are caused by the different characteristics of the individual itself. External factors are differences in spatial ability caused or manifested by external factors. Internal differences include: biological factors, other ability(Froiland & Davison, 2020), emotion/attitude(Cooke-Simpson & Voyer, 2007; Lennon-Maslin et al., 2023; Moè, 2009). External factors include social factors, measuring tools and measuring methods(Maeda & Yoon, 2012; Peters, 2005). Ellipses are used in the figure because there may be other factors that influence spatial ability that are not explored or understood. Biological factors include genetic factors(Hausmann et al., 2000; Thomas & Kail, 1991), neurological development(Hao et al., 2016; Li et al., 2019), gender differences, and age differences(Yan et al., 2023). Social factors include environmental factors(Cherney, 2008; Quaiser-Pohl et al., 2006), culture and education(Tian et al., 2022), training and practice.

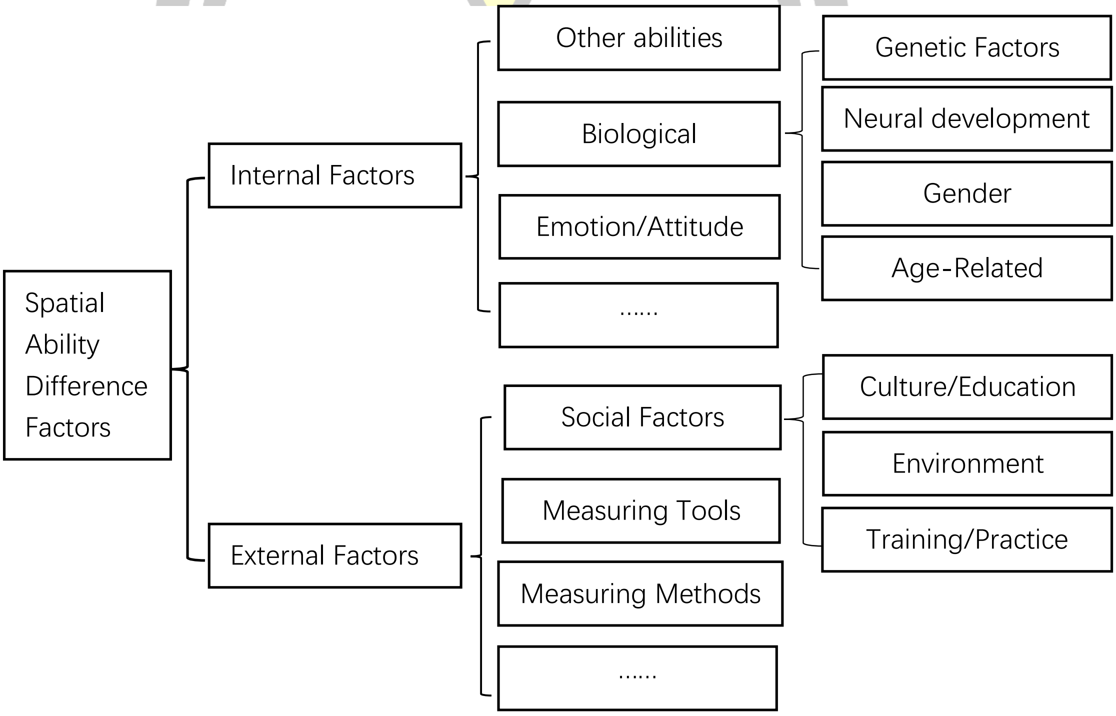


Figure 4 Factors of Difference in Spatial Ability

Gender differences are a well-studied area of psychology, with gender differences in spatial ability receiving much attention, and most research supporting greater spatial ability in male (Lauer et al., 2019; Lee et al., 2019; Patkin & Dayan, 2013). Multiple meta-analyses of various tests of spatial ability have found that mental rotation is widely recognized as the cognitive ability with the greatest gender differences(Hyde & Linn, 1989; Linn & Petersen, 1985; Voyer et al., 1995). However, Bartlett & Camba (2023) “argue that the construct of ‘spatial ability’ itself has been co-constructed with gender, and thus has not been devised in a neutral way, but in a manner that is influenced by gender beliefs.……Spatial ability has been emphasized in masculinized disciplines, while the role that spatial ability plays in feminized disciplines like garment construction, sewing, ceramics, interior design, domestic jobs, nursing, sonography, etc. has been largely ignored." However, due to the uncertainty of the definition and classification of spatial ability, there is still no better tool to accurately measure individual spatial ability. Therefore, gender difference is still introduced in this study, but more attention is paid to social factors, such as the background and experience of the research subjects in the pre-test and demographic survey. Study on the change of visual spatial ability of students after course training in post-test. As Bartlett & Camba (2023) suggested, "Instead of gender, it makes sense for spatial researchers to group people based on other criteria such as past background experience, since this is a factor that is likely to directly contribute to differences in spatial ability. For example, researchers may decide to group novices versus experts, people who have not taken a geometry class versus people who have, etc. This research method can more precisely help us understand what experiences might contribute to certain spatial skills."

2.2 Development of Spatial Ability

2.2.1 Can Spatial Ability be Improved

Malleability is a central question in the study of developmental and educational psychology, such as can experience change a person's ability? How does it work? Will that change over time? Are there critical periods that affect ability development? What are the causes and determinants of environmental differences among individuals? These are questions that academics have been studying and exploring to maximize human potential. One of the research focuses on improving ability in subject education, covering different subjects such as mathematics, chemistry, science and engineering, and reading(Uttal et al., 2013). From the above analysis of differences in spatial ability and related factors, it can be seen that differences in spatial ability are more influenced by controllable factors, especially social factors, in addition to irresistible factors such as genetic factors. For example, the difference in spatial ability caused by age difference can be explained as follows: with the increase of age, individuals are affected by social factors (such as spatial experience), which leads to the difference in spatial ability at different ages. This study focuses on the improvement of spatial ability, that is, whether spatial ability has plasticity, and whether 3DMP teaching or training is an effective means to improve spatial ability. Therefore, the focus is on the social factors of spatial ability, and the object is college students in the adult stage (there is ample evidence that spatial ability is plastic in both adults and adolescents, but compared with adults, the cognitive thinking of primary and secondary school students under 13 years old is more plastic(Heckman & Masterov, 2007)).

Researchers hold different views on whether and how spatial ability can be developed. Although some cognitive scientists believe that spatial ability cannot be improved, a large body of research shows that spatial ability can be improved through space activities and training. However, researchers do not agree on what type of experience and how long it takes to improve spatial ability. Sexton(1992)pointed out that it is indeed possible to improve spatial visualization ability if the teaching is appropriate and the training time is sufficient. Braukman's research (1993) also shows that 18 hours of engineering graphics teaching can significantly improve spatial visualization. Saito et al.(1994) believe that descriptive geometry and computer graphics courses can improve students' spatial skills. Field(2007), on the other hand, believes that using sketches in the course can improve spatial visualization skills. Smith et al.(2001) describe visualization as a skill that can be learned, developed, and improved with appropriate guidance and methods. Eliot et al.(1984) pointed out that although the idea that spatial ability can be trained in the classroom has not been tested, the idea that work experience can improve spatial ability has been widely supported.

In previous theoretical and empirical studies, the interpretation of spatial ability is a spatial cognitive processing process involved in spatial ability testing, and the research focuses on how people psychologically convey and process spatial information when performing spatial cognitive tasks. The individual differences in spatial ability are mainly reflected in the differences in spatial ability performance in spatial cognitive tests, and the performance of spatial ability depends on the basic spatial cognitive processing, including the encoding of visual stimuli, the construction of mental images, the transformation of mental images in working memory, and the comparison between visual stimuli and mental images. Combining theories of mental imagery and working memory, cognitive psychologists gain a deeper understanding of spatial ability by analyzing individual differences in the basic spatial cognitive processes involved in spatial ability tests(Hegarty & Waller, 2005). Education level has a significant impact on spatial ability, especially on individual differences. In Kosslyn et al. 's theory and empirical research (2011; 1990; 1995) on visual spatial cognitive processing, individual differences in spatial ability are interpreted as being influenced by differences in individual mental representation ability. For example, the level of spatial imagination depends not only on the efficiency of mental rotation, but also on the quality of mental representation generated by corresponding visual stimuli. However, there are individual differences in the efficiency of mental rotation, and the quality of mental imagery is also limited by the capacity of the individual visual processing system(Fischer et al., 1994; Hegarty & Waller, 2005; Lohman et al., 1987). A series of studies on visual spatial cognitive processing suggest that some spatial activities do have practice effects, that is, some spatial ability can be improved through training, such as mental rotation and pattern recognition(Li, 2000). Teaching and training aimed at improving spatial ability can improve spatial ability and produce lasting positive effects, and can also be transferred to non-targeted training spatial ability(Uttal et al., 2013).

One of the key issues of early studies on spatial ability is the gender difference in spatial ability and the degree of difference (Linn & Petersen, 1985; Maeda & Yoon, 2012). Some studies suggest that gender differences in spatial ability between boys and girls are caused by differences in spatial cognitive strategies used to solve spatial problems. Sherman(1967) believes that gender differences in spatial ability are social and related to the social experience and environment involved in spatial activities. Boys perform better than girls in academic and professional performance in many subjects(Baenninger & Newcombe, 1989). This difference is attributed to the fact that teaching and training in spatial activities, such as geometry lessons, drawing, building block games and physical activities, are more geared towards boys and do not provide girls with more spatial experience(Fennema & Sherman, 1977). Some studies have also found that both boys and girls who often participate in the teaching and training involving spatial activities can improve their spatial ability, but girls with low spatial ability need longer time to improve the same ability than boys with high spatial ability. In other words, in the limited teaching and training time, the improvement of girls' spatial ability will be smaller than that of boys(Terlecki et al., 2008).

2.2.2 Ways to Improve Spatial Ability

With more and more attention paid to spatial ability in subject education, the focus of research has turned to how to improve spatial ability through teaching or training, and what is the effect? Will there be a transfer of learning? Will this uplift change over time? Research around these issues has had a positive impact on the sustainable development of educational policies and teaching interventions.

Studies on spatial ability improvement have found that teaching and training oriented to spatial ability improvement can improve spatial ability more than mere participation in space activities (Baenninger & Newcombe, 1989; Höffler, 2010; Shea et al., 2001), and there are various kinds of spatial ability improvement. The simplest way is to directly ask students to practice specific spatial ability test questions repeatedly to get a good score on the spatial ability test. This method is short in duration, usually lasting a few days or weeks. The second way is to use course teaching to improve spatial ability. The teaching content ranges from teaching how to solve spatial ability test questions to teaching and learning activities or course learning tasks that strengthen spatial activities. Compared with the first method, the second method lasts longer, ranging from several classes to a semester or more; There are more diverse forms of training, such as measuring training specifically for a specific spatial ability, such as short-term teaching training for mental rotation, or integrated into disciplinary courses, such as information technology courses, labor technology courses and integrated practical activities courses. Studies on the first method found that training specifically for specific spatial ability tests can improve the performance of specific spatial ability tests, but it is difficult to improve other spatial ability tests without targeted training (Bethell-Fox & Shepard, 1988; Cohen & Hegarty, 2014; Lohman & Nichols, 1990), and the improved spatial ability can only be maintained for a short period of time. The study on the second method found that integrated subject courses can provide more space to improve the activities or learning tasks of teaching and learning, but the class time must be no less than three weeks. The more specific the teaching of the courses for spatial ability improvement, the better the performance of the spatial ability assessment. The National Research Council (NRC)'s "Learning to Think Spatially" report(Council et al., 2005) advocates the research and practice of teaching methods that can improve spatial competence in general.

In addition to the above two methods of teaching and training, the application of computer simulation can also improve spatial ability. Computer simulation refers to a computer program used to simulate a specific system model, that is, to create a mathematical model or a descriptive model of an object. Computer simulation is different from computer-animation. The basic feature of computer simulation is that people interact with the simulation program running on the computer. A typical computer simulation is Video-Game. Research on video games has found that the use of video game applications can significantly improve students' spatial ability, especially for those with relatively poor spatial ability(David, 2012). Emerging ICT technology has a great impact on the application of electronic games, such as the 3D Puzzle Video Game, which changes the spatial dimension of electronic games. As a new means to improve students' spatial ability(Lin & Chen, 2016), 3D visualization technology has attracted much attention as the most promising innovative way (Lee et al., 2009). It is a high-end human-machine interface system integrating simulation technology, computer graphics technology, multimedia technology, sensing technology and network technology. Create a dynamic, three-dimensional geometry world that allows users to interact with objects in the virtual world (the simulated natural world) in a natural way. For example, 3D CAD uses computer programs to produce and simulate the physical design, showing the appearance, structure and other characteristics of the physical process; Virtual Reality (VR) provides real-time simulation and real-time interaction of multi-sensory experiences such as sight, hearing, touch, smell and taste.

In addition, studies on spatial ability transfer believe that effective curriculum teaching involving rich spatial activities and interaction can promote spatial ability transfer (Kozhevnikov & Thornton, 2006). However, the subject expertise involved is specific to specific subject areas, such as chemistry and geographical sciences, which will affect the migration in other subject areas(Bartlett & Camba, 2023). So how to improve spatial ability through effective curriculum teaching without affecting the learning of specific subject knowledge and skills needs further exploration.

In addition to the above specific training ways, American psychologist McKim(1980) proposed the training method of image thinking from the perspective of thinking training. He believes that image thinking relies on three kinds of visual imagery (observation, imagination, construction): first is "the image that people see", the second is "what we imagine through the window of our hearts", and the third is "what we paint is graffiti or painting". He further pointed out that experienced visual thinkers are able to use all three images flexibly and interactively. Figure 5 shows the interaction of the three images. Among them, the observation image and the construction image overlap, which reflects that the observation can promote the construction, and the construction also strengthens the observation; The construction image and imagination image overlap, reflecting that construction image can stimulate and promote imagination, and imagination also provides material for construction image; The imaginary image and the viewing image partially overlap, reflecting that observation can provide raw materials for imagination, and imagination can provide targets for observation and filter the observed elements. Based on the above theories, McKim(1980) suggested that in the training of image thinking, it is necessary to consider how to effectively combine the correlation of "Seeing", "Imagining" and "Drawing" to stimulate learners' inner perception. In the "Creative Thinking Training Course" offered by him in Stanford University, he carryed out the training of "imagining and drawing", requiring students to see, think and draw organically.

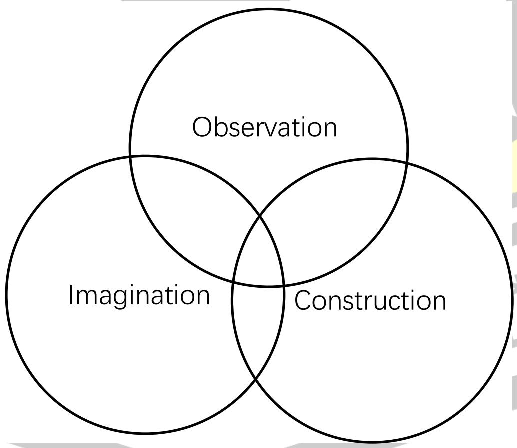


Figure 5 Mckim's Image Thinking Model

2.2.3 Spatial Ability Improvement in Subject Education

In the Next Generation Science Standards (NGSS) published by NRC(2013), the interpretation of core concepts of many disciplines involves spatial content and information representation with spatial characteristics. Most of the problems required to be solved are to explore objects and their states in the real world in three-dimensional space (even in the absence of relevant physical objects). The understanding and solution of these problems usually require a clear spatial relationship of objects. The information with spatial characteristics is processed by mental representation(Ganis et al., 2008; Gilbert, 2005). Studies have shown that students who have problems with spatial ability have difficulties in science, technology, engineering and mathematics, and that this effect is long-lasting, so that they are more inclined to switch from these subjects to other subjects(Uttal & Cohen, 2012). It can be seen that in subject education, educators and researchers need to understand the impact of spatial ability on students' subject learning, and improve students' spatial ability so that they can meet the academic and career needs of the subject(Wai et al., 2009).

At the university level, courses to improve spatial skills are often found in STEM majors or disciplines. Many disciplines clearly require the use of space ability to understand and solve subject problems. For example, Earth education contains rich space elements, and it is clearly pointed out in the teaching content knowledge guidance and evaluation that space ability should be used to describe and understand complex subject content, analyze and process two-dimensional or three-dimensional spatial information (Jadallah et al., 2017; Kastens et al., 2014). Spatial information systems like GIS are used to input, store, query, analyze and display geographic data; Mathematics education includes the understanding of the concept of space, the understanding of the motion, transformation and position relationship of two-dimensional or three-dimensional spatial geometric figures, as well as the combination of number and shape, geometric interpretation of algebraic problems, etc. To improve the spatial ability in subject education, educators need to enhance the traditional subject curriculum teaching through curriculum teaching design, help students improve their spatial ability, and make the development of spatial ability sustainable and transferable(Newcombe, 2010). The main way to use is graphic education, and the most common graphic education course is Descriptive Geometry (DG). With CAD replacing manual drawing, drawing tools have changed dramatically. Computer drawing programs can be used to generate a variety of geometric shapes, including the modeling of curves, surfaces, and solids. This has a great impact on graphics education. Compared with manual drawing, CAD is more attractive to students because it can help students render and generate high-quality graphics (Peña et al., 2016). Whether CAD can replace manual drawing to improve students' spatial ability has also become a research trend in graphics education.

In the era of new technological revolution, emerging technologies are updated frequently, and effective teaching needs to provide diverse and interdisciplinary comprehensive knowledge. Education circles at home and abroad are actively taking measures to bridge the gap between school science and technology education and social science and technology innovation talents. In order to let students understand and master advanced technology and improve innovative design ability, the comprehensive practical activity course of "creative materialization" has been implemented. The specific goals include: "Use certain operational skills to solve problems in life, put certain ideas or creativity into practice, make and continuously improve more complex products or supplies through design, production or assembly, develop practical innovation awareness and aesthetic awareness, and improve creative realization ability." Through the learning and practice of information technology, improve the ability to use information technology to analyze and solve problems as well as the ability to design and make digital products. In the design and production activity unit of information technology and labor technology, the recommended topics such as 3D CAD design and preliminary application of 3D printing technology, design and production of model projects, 3D fun design, arbitrary transformation of 2D and 3D views and initial experience of open-source robots all involve 3D design and production. From the actual situation, the school designs the specific content and organizational form of comprehensive practice activities.

As mentioned above, the DG course, D&T (Design & Technology) course and comprehensive practical activity course, which include spatial content, have indirectly achieved the improvement of students' spatial ability. However, in most subject education, with the exception of a few subjects such as mathematics and geography, spatial development is usually not an explicit curriculum objective.

In subject education, improving the ability of young people through teaching practice and training is crucial to their achievement in adulthood. Spatial ability has been recognized as an important subject ability in subject education, which plays an irreplaceable role in the promotion of subject domain knowledge and scientific and technological innovation(Hinze et al., 2013; Shea et al., 2001; Stieff & Uttal, 2015). In the exploration of geography and physics, it is found that spatial ability has a positive impact on the understanding of kinematic schematics with spatial relationship representation (Kozhevnikov & Thornton, 2006). In the exploration of mathematics, it is found that students of different spatial ability levels and ages have achieved effective mathematical academic improvement through teaching and training (Cheng & Mix, 2014; Jee et al., 2013). The teaching of graphics courses has improved the situation that students' academic performance is not up to standard due to their low spatial ability, and they even choose not to engage in careers in related disciplines, and explored the feasibility of improving academic performance by improving students' spatial ability(Dimitriu, 2015; Uttal et al., 2013).

Uttal et al. 's meta-analysis(2013) found that spatial ability can be improved and produce lasting positive effects in different learning segments, and proposed that spatial ability improvement should be included in subject curriculum teaching. For more than 10 years, Dr. Sorby from Michigan Technological University in the United States has been committed to the application research of spatial ability improvement of students in the field of science, engineering and technology, and has used 3D visualization technology to enhance the representation of multi-sensory information such as vision, hearing and touch to improve students' spatial ability (Sheryl A Sorby, 2009). Sorby conducted a longitudinal study, which modified the university curriculum for improving spatial ability into the middle school curriculum. The research results show that this course is suitable for improving the spatial ability of middle school students, especially girls in middle school, and has a positive impact on students' future math and science course selection (Sheryl A. Sorby, 2009). Some studies have improved spatial ability through interdisciplinary engineering practice activities, such as engineering design activities and construction and assembly activities. Studies have also observed spatial cognitive activities involving teachers and students, learning objects and interdisciplinary learning environments, such as spatial discussion, gestures, physical manipulation, analogy, assembly according to drawings and drawing, etc. The research believes that these spatial cognitive activities not only promote the improvement of spatial ability, but also promote the improvement of spatial ability. It also improves the learning ability of subject area knowledge and problem-solving ability (Göksun et al., 2013). Effective teaching and training can improve spatial ability in a variety of ways, such as puzzles, blocks, origami, board games and video games (Doyle et al., 2012), as well as physical training involving physical manipulation in three-dimensional space, such as wrestling(Moreau et al., 2012). Different teaching and training methods have different impacts on the improvement of spatial ability. Some have obvious short-term effects but no transfer of learn(Borst et al., 2011), while others make spatial ability development sustainable and transferable(Terlecki et al., 2008). Some studies suggest that teaching and training including visual-spatial cognitive activities can well promote the improvement of low spatial ability, and it is more effective for high spatial ability(Kyllonen et al., 1984). There are also studies that suggest that people with low spatial ability can improve more, but not reach high spatial ability level(David, 2012) . Other studies suggest that teaching and training may not be effective for everyone, but only for people with low spatial ability, especially women(Geiser et al., 2006).

To sum up, effective teaching and training can realize the improvement of spatial ability and the learning of subject knowledge, and effective teaching should not only enable students to master different types of subject domain knowledge such as factual knowledge, conceptual knowledge and procedural knowledge, but also improve students' spatial ability. The key to achieve this is to create teaching and learning situations that include spatial cognitive activities. Because thematic activities with specific subject context have significantly higher effects than abstract teaching (Mohler & Miller, 2008). In addition, in the actual classroom teaching environment, many other teaching and learning factors should be considered, such as class size, teaching mode, available teaching resources and so on.

2.3 Theoretical Framework

2.3.1 Visual Spatial Cognition Theory

2.3.1.1 Visual Imagery

Kosslyn, an American psychologist, neuroscientist, and expert in learning science, found that the most commonly used mental Imagery of people in their daily lives is visual imagery (Kosslyn, Seger, et al., 1990). Kosslyn et al. believe that visual imagery is the image "seen" in the mind without corresponding sensory input, and it is the perception of memory information or the perception of external input information such as words or ideas (Kosslyn, 1988; Osherson & Kosslyn, 1995). All the features of the "seen" image depend on the similar perception in the same mode, so that people often only need to pass one sensory channel to obtain the required sensory stimulation for multi-sensory mental imagery(Nagy-Kondor, 2016). Visual representation does not present a fixed image, but stores the information needed to form an image in memory, and uses this information to create an image in a specific context, so that the image can be "seen" in the mind and the shape and other properties of the generated image can be interpreted (Osherson & Kosslyn, 1995).

2.3.1.2 Visuospatial Thinking

Visual thinking refers to the cognitive ability to present and explain mental imagination through simple and meaningful visualizations such as drawing. Visual thinking is a way of communicating complex, latent, vague ideas that can be externalized with the help of visual thinking tools such as pen and paper and computer software. Visual thinking is an important ability to develop new designs and create new artefacts, realize innovations, effectively communicate these innovative ideas with others, and work together to make them a reality in the professional practice and learning of the subject field. The cultivation of visual thinking is the key to the improvement of creativity and communication ability.

This study focuses on visuospatial thinking, which is closely related to professional practice and learning in subject areas. Visuospatial thinking mainly refers to the cognitive ability of people to convey and process visual and spatial information. The mental representation of visual objects containing visual and spatial information is constructed, transformed and interpreted, and visuospatial thinking activities start from visual perception and memory, which can promote the smooth completion of other cognitive activities in the psychological processing. Visual representation plays an important role in the execution of visuospatial thinking (Burton, 2003). For example, navigation map browsing, mechanical construction blueprints interpretation and other diversified visual objects are invented and created to enhance human cognition. They all use graphics to describe and analyze the inherent spatial relationships contained in them, which can reduce cognitive load and improve spatial cognitive ability in visuospatial thinking(Jadallah et al., 2017).

2.3.1.3 Visual Object Recognition

Among the research theories related to visual object recognition, Feature-Analysis theories propose that visual stimuli are composed of a limited number of features or components, each of which is a distinguishable feature. In the process of visual object recognition, the psychological process will compare the external visual stimuli with the existing knowledge stored in human memory. The feature analysis theory explains relatively simple and intuitive visual object recognition, but the visual objects in the real world are relatively complex. For the recognition of complex visual objects in human daily life, the Recognition-By- Component theory provides a three-dimensional visual object recognition method. The theory of component recognition proposes that complex visual objects under a specific perspective can be represented by the combination of basic three-dimensional geometric shapes (Osherson et al., 1990). Based on the theory of component recognition, the Viewer-Centered-Approach proposes that humans store and remember multiple three-dimensional graphics representing visual objects from different perspectives. When observing a visual object from a certain perspective, if it cannot match all the 3D graphics representing the visual object stored in the memory, it is necessary to carry out mental representation of the visual object until it can match the 3D graphics representing the visual object stored in the memory. The results of research on visual object recognition, psychology and neuroscience are consistent with the interpretation of feature analysis theory, component recognition theory and observe-centered theory(Matlin, 2013). With the deepening of the research on the recognition of complex visual objects, the research methods used are becoming more and more complex, and the theoretical explanations are becoming more and more detailed.

2.3.1.4 Visuospatial Cognition

Visuospatial cognition is mainly the identification of visual objects and the representation of spatial relations (Kozhevnikov et al., 2013). In visuospatial cognition, it is necessary to be able to generate the "seen" image in the mind, and to be able to carry out spatial geometric transformation in a certain way, mainly including the image shift, rotation, scaling and mirror transformation. According to Kosslyn et al. 's visuospatial cognitive processing theory, visuospatial cognitive processing mainly involves object rotation, motion inference, image scanning, spatial relationship recognition and visual feature extraction based on mental imagery. This series of visuospatial cognitive processing ability is considered to be the core component of spatial ability(Kosslyn, Seger, et al., 1990). As a typical spatial cognitive processing process based on mental imagery, mental rotation refers to the shape representation of objects or graphics after rotation at a certain Angle in the mind, such as the mental representation of letters, two-dimensional graphics and complex three-dimensional objects in different directions.

2.3.1.5 Visuospatial Cognition based on Working Memory

According to the working memory model of British psychologist Baddeley, working memory includes several independent subsystems such as visuospatial processing system, language processing system, central executive system and plot buffer(Baddeley, 2020). The visuospatial processing subsystem is named Visuospatial-Sketch-Pad, or Spatial-Working-Memory, and is responsible for the immediate storage and processing of the limited amount of visual and spatial information currently processed. Some studies on visuospatial working memory suggest that there are individual differences in the performance of spatial ability including spatial imagination and spatial relations, that is, there are differences in the execution of individual visuospatial working memory systems (Miyake et al., 2001). Further studies believe that spatial cognitive tasks containing complex visual and spatial information will affect the performance of spatial ability, such as the parallel spatial cognitive processing of rotation and shift at the same time will lead to working memory overload (Isaak & Just, 1995).

2.3.2 Multimodal Theory and Multimodal Learning

2.3.2.1 Multimodal Theory

Understanding how humans perceive and process information is critical to better understanding student cognitive development. Kellough et al. (Kellough, 2010)found in their research that, people have personal preferences when they perceive and process information, and these personal preferences have an impact on students' learning. The relevant researches include multimodal, multi-representation, multi-intelligence and differentiated teaching. This research focuses on multimodal theory and multimodal learning.

From the perspective of brain neuroscience, multimodality refers to multiple sensory organs and the nervous system that processes each sensory information. Multimodal sensory systems include sight, hearing, touch, smell and taste. From the perspective of social semiotics, multimodality refers to the simultaneous and mixed use of symbolic resources or symbolic languages that can produce meaning. Multimodal symbol resources and symbol languages include text, images, video, audio, sensor data, facial expressions, gestures, colors, and even hair and makeup. The multimodal symbolic system is intrinsically related to the multimodal sensory system, because the human brain needs to call the multimodal sensory system when processing the information composed of the multimodal symbolic system.

Bruner, influenced by Piaget's theory (Piaget & Inhelder, 1956)of stages of cognitive development, proposed that children's cognitive development level is represented by changes in the mode of representation(Bruner & Studies, 1967). Representational modality is the way people perceive and know the world. Bruner believes that there are three main representational modes, which are respectively enactive mode, iconic mode and symbolic mode according to the order of development. These three representational modes have their own characteristics in representing knowledge, experience and thinking, and individuals will use different representational modes under different conditions. Action modality refers to the acquisition of representational knowledge, experience and thinking through appropriate action. The most common is kinesthetic modalities. Children are able to manipulate familiar and confidence-inspiring objects to complete various motor tasks, and encode their behavioral information and store it in memory. Symbolic modality refers to the acquisition of representational knowledge, experience and thinking using images or imagery. The most commonly used symbolic mode in daily life is visual imagery. Symbolic modality refers to the acquisition of representational knowledge, experience, and thinking using abstract symbolic systems, which are stored in the form of language, words, numbers, music, or other symbolic systems. Symbolic mode is the most used mode in school at present. In class, various symbols are basically used to represent and convey knowledge and experience. For example, students of different classes will use graphic textbooks to systematically learn knowledge and experience of various subjects.

The relationship between modal and media is essentially the relationship between discourse and technology, and there is an inherent connection between the two. Modal is the way to express information using specific media, while media is the physical tool to convey information. When people feel the objective world, they need to use the multimodal sensory system to perceive the information composed of the multimodal symbol system. Among them, eyes, ears, nose, mouth, hands, etc. are the sensory organs of the human body, and the paper and pen used for writing and drawing, traditional chalk chalkboards, electronic whiteboards, loudspeakers, projectors, and computers are described as the extension of human body organs. Moreover, one medium can represent different modes, and the same mode can be represented by different media. In person-to-person and person-to-system interactions, a mode can be used at the input end (from person to system or other person), or at the output end (from system to person or to another system), or both. Kress puts forward three viewpoints on multi-modal information transmission in the classroom: First, the media can convey meaning according to the different needs of teachers and students, and form a mode of expressing meaning; Second, various modes such as language, text and images can be mixed to produce meaning in the process of social interaction; Third, in order to meet the needs of society to convey information, existing modes will be transformed to create new modes (Kress & Van Leeuwen, 2001).

2.3.2.2 Multimodal Learning

Samples et al. 's study(1992) finds that although students have their own preferred learning modalities, they generally adopt multi-modal approaches based on the learning scenarios they are in. Moreover, Samples' research results also show that multi-representational modal teaching can positively influence students. For example, it improves the self-concept of students who do not perform well in the traditional classroom teaching environment. The development of people from one mode to the simultaneous use of multiple modes is inseparable from social processes. With the development and application of computing science, people's grasp and use of different symbolic characteristics in the expression of meaning are multi-modal. Different modes can be used to express the meaning of the same discourse, such as words, images, music and movements, which can be used separately or combined.

In general, one or two modes are the main body in this variety of representational modes, and the rest are complementary. By making use of the complementarity between various modes, the redundancy between various modes is eliminated and multiple modes are used synchronously better. Gu, Y.G. (2007) analyzed the multi-modal learning process of students through the constructed learning behavior model and put forward five hypotheses for reference in related research. Among them, in the multimodal learning based on traditional text textbooks, hypothesis 1 and Hypothesis 2 about modal transformation believe that the modal transformation in the learning process needs to invoke the relevant resources in the students' personal knowledge base, and appropriate modal transformation will enhance the students' meaning construction. In multi-modal learning based on computer multimedia, hypothesis 3, Hypothesis 4 and Hypothesis 5 on memory ability believe that multi-modal learning can enhance memory ability more than single-modal learning, and the former with higher socialization is more conducive to enhancing memory ability than the latter.

In addition, in the study of multimodal social activities, some social interaction processes have few sessions but numerous changing participant structures and identities. In this regard, different from dialog-centered discourse analysis, Levine & Scollon(2004) proposed that convenient video recorders and material extraction techniques could be used to study various social interaction processes. Video recording can last for hours, and today's technology and software can analyze events over an entire semester or school year, better allowing for a periodic process analysis. Educational Data Mining (EDM) is an interdisciplinary field that uses data mining techniques to study and analyze data in the education domain. Its goal is to extract valuable insights from the vast amount of data generated during the educational process to improve educational practices, support student learning, and make informed educational decisions. Combined with some unique technologies (such as xAPI), it can help practitioners in the field of education to better understand and grasp the needs of academic spatial ability improvement, and help realize personalized education and more effective education methods(Wu et al., 2019).

2.3.2.3 Multiple Representation Modes for Spatial Ability Improvement

In daily life, study and work, people need to solve many practical problems including visual object recognition and spatial relation representation. The research of cognitive psychology shows that when people perceive and recognize the external world, they need to invoke the multi-modal sensory system to perceive the information composed of the multi-modal symbol system and establish the mental representation of the spatial characteristics and attributes of things(Wickens et al., 2021). According to the types of representational modes proposed by Bruner (1967), kinesthetic modes, visual imagery and symbolic modes are commonly used in visual-spatial cognitive activities, and multiple representational modes are used simultaneously, that is, multiple representational modes are adopted. These visual spatial cognitive activities, which contain multiple representational modes, mainly include space description, gesture, multi-view rendering, three-dimensional entity modeling, and physical object making.

Spatial description refers to the use of mathematical language and tools to express spatial concepts and describe laws(Pruden et al., 2011). The concept of space is used to describe the spatial characteristics and attributes of objects(Cannon et al., 2007), that is, the mathematical term describing two-dimensional or three-dimensional objects and Spaces, which can be divided into four types: one is about shape, that is, describing the geometric forms of two-dimensional or three-dimensional objects and Spaces, such as circles, triangles, polygons, cylinders, spheres, cones, pyramids, rings, etc. The second is about size, that is, describing the size of two-dimensional or three-dimensional objects and Spaces, such as large, small, long, short, high, whole, half and so on; The third is about orientation, that is, describing the position of two-dimensional or three-dimensional objects and empty, such as middle, forward, above, behind, far, near, side, translation, rotation, etc. The fourth is about spatial characteristics, that is, describing the characteristics and attributes of two-dimensional or three-dimensional objects and Spaces, such as lines, curves, edges, planes, center of a circle, bending, symmetry, etc. Relevant studies have found that in the process of spatial description, students who use more spatial language perform better in solving spatial problems, and there is a significant positive correlation between the rich use of spatial language and the improvement of students' spatial ability(Pruden et al., 2011). The reason is that the use of spatial language prompts students to shift their attention from simply focusing on objects and space itself to consciously focusing on the spatial characteristics and spatial relations of objects, which enhances their spatial language application ability and improves their spatial cognitive processing skills.

Gesture refers to the representational gesture that can convey the spatial characteristics and attributes of the object along with language (Chu & Kita, 2011). It is a common way to convey spatial information. For example, gesture describes the change or process of the relative position of people and the space they are in, and describes the spatial layout and irregular shape of buildings. Gestures that are the practice of spatial perception can be roughly divided into two categories, one is Representational-Gestures and the other is Beat-Gesture. Relevant studies have shown that representational gestures can enhance spatial ability and improve spatial problem-solving ability(Alibali et al., 2011). Relevant studies have found that students with low spatial ability use more gestures to describe and explain their ideas than students with high spatial ability. Further research and analysis have found that students with low spatial ability use gestures to convey more static spatial information, while students with high spatial ability convey less dynamic spatial information (Göksun et al., 2013; Newcombe & Shipley, 2014).

Sketching does not need to provide physical objects, but supports the visual spatial cognitive activities of visual representation of physical objects through drawing, which is widely used in engineering technology, art and other fields. Elements of multi-view rendering include Lines and Lettering. Lines include line segments, circles, arcs, and splines. Graphic text includes symbols, dimensioning and text annotations. There are three methods for drawing multi-view view: freehand drawing, hand-held drawing tool assisted drawing and CAD. Compared with the spatial description and gesture mentioned above, multi-perspective view rendering can not only provide more detailed description of spatial features and spatial relationships, but also promote the creation of mental imagery, especially visual imagery, more significantly and promote the improvement of higher-level spatial cognitive processing (Gottschling, 2006).

Three-dimensional Solid Modeling (3D Modeling) is a spatial cognitive activity that supports the visual representation of solid objects by constructing geometric models. 3D solid modeling is widely used in engineering technology, art and other fields. The models created can be either real objects in the real world or fictional things. They can be as small as molecules and atoms in the micro world, or as large as galaxies and universes in the macro world. 3D modeling (3D CAD) is the core content of modern graphics education curriculum, which makes full use of 3D spatial feature information (size, shape, motion orientation and other visual spatial elements) to achieve 3D visual experience, optimize visual spatial cognitive load, and enhance visual representation ability. A course design study on spatial ability improvement confirmed that creating 3D solid models using 3D CAD can help improve spatial cognitive processing ability (Mart ń-Dorta et al., 2008).

Physical production (3D printing). Physical fabrication is the creation of physical prototypes using materials such as clay, modeling wax, glass, wood or metal to present and interpret the mental representation of the designed physical object. Physical Manufacturing methods include Cutting, Subtractive Manufacturing, Forming and Additive-Manufacturing. The latest research believes that the use of emerging rapid prototyping technology such as 3D printing can design and produce 3D solid prototypes in a short time, which has the potential to improve spatial visualization skills(Katsioloudis et al., 2014). In addition, touching and observing objects through building blocks, etc. can promote spatial perception more than observing solid models only through screens(Sheryl A Sorby, 2009), and physical operations in reality are synchronized with virtual operations on screens in real time, which has a significant change effect and is more popular among students(Vander Heyden et al., 2017).

2.3.3 Cognitive Development Theory (Constructivism)

2.3.3.1 Cognitive Development Theory

Cognitive development theory refers to a series of psychological theories about how cognitive ability in children and adults develop over time and with experience. These theories aim to explain the evolutionary processes of human thinking, learning, and problem-solving, as well as how people acquire knowledge, understand the world, and adapt to their environment. In the field of cognitive development, several renowned theories have been proposed, including:

Piaget's Cognitive Development Theory: Piaget(1974; 1956) was one of the pioneers in the field of cognitive development, and he introduced the well-known theory of cognitive development consisting of four stages. These stages include the Sensorimotor Stage, the Preoperational Stage, the Concrete Operational Stage, and the Formal Operational Stage. He believed that children establish cognitive structures through active engagement with their environment.

Vygotsky's Sociocultural Theory: Vygotsky(1978) emphasized the significance of the sociocultural environment in cognitive development. He argued that children acquire knowledge and cognitive ability through interactions with more experienced individuals and through cultural tools such as language. His theory highlights the close relationship between social interaction and cognitive development.

Jerome Bruner's Constructivist Theory: Jerome Bruner's constructivist theory(1966; 1967) underscores that learning is an active process achieved through individuals' interactions with their environment. He maintained that knowledge construction is based on individual experiences and cultural backgrounds.

These cognitive development theories offer various frameworks and perspectives for understanding the cognitive development process in humans. Different theories emphasize different factors, including biology, the sociocultural environment, information processing, and their impact on cognitive development. These theories help educators, psychologists, and parents better comprehend the cognitive development of children and adults, enabling them to provide education and support tailored to different developmental stages.

In his research on the development of children's spatial concepts, Piaget(1956) divided spatial concepts into three parts based on geometric concepts: Topological Space, Projective Space, and Euclidean Space. Topological space involves relationships within objects, and these relationships remain unchanged regardless of changes in the shape of objects. Euclidean space deals with relationships between different objects in space and is subject to changes as objects' shapes change. Projective space involves perspective or observing the contours of objects from different positions and angles. Based on their research on these three types of spatial concepts, Piaget and Inhelder (1956) proposed the primacy of topology, arguing that topology should be constructed first, followed by Euclidean space and then projective space.

2.3.3.2 Constructivism

Constructivism is an important branch of behaviorism that posits that individuals actively construct their mental representations of reality based on their experiences, interactions, and prior knowledge. As both a learning theory and educational philosophy, constructivism offers a series of explanations for teaching and learning. In terms of its epistemological perspective, it emphasizes the dynamism of knowledge, asserting that knowledge is the result of individuals' continuous exploration and construction through interactions with others or their surrounding environment. In terms of its pedagogical view, it stresses learner-centered teaching, starting from the learner's experiences. Regarding its perspective on learning, it emphasizes the constructive nature of learning. Constructivist learning theory identifies four key elements in the formation of a learning environment: "context," "conversation," "collaboration," and "construction." It is generally believed that learning is the active process of constructing meaning by learners themselves. They do this by actively processing and manipulating new knowledge, often with the help of peers, within a specific situational context.

Different constructivist schools of thought may emphasize different aspects, but the following three broad principles can help explain them:

(1) Individual Construction of Understanding: The fundamental principle is that learners construct their understanding of things in their own ways, and different individuals may hold various interpretations of the same concept. Thus, there is no single or standardized understanding of things. This principle was initially proposed by Kant(1893) and later adopted by Dewey(1986).

(2) Piaget's Developmental View: This perspective, often associated with Piaget(1974; 1956), argues that children progressively construct knowledge about the external world through interactions with their surrounding environment. For Piaget, development is not driven by internal maturation or external instruction but is an active, constructive process in which individuals establish increasingly differentiated and integrated cognitive structures through their own activities.

(3) Vygotsky's Social Constructivism: Vygotsky(1978) is the foundational figure in social constructivist theory. Social constructivism also views learning as an individual's construction of knowledge, but it places a stronger emphasis on the social aspect of the construction process. It contends that learning occurs in a social context, with interactions among learners and peers being essential components of the learning process.

Constructivism encompasses a variety of perspectives, but most constructivists agree on several key points: (1) learning is an active process in which learners construct mental representations, emphasizing learner agency; (2) learning involves both the construction of meaning from new information and the transformation and reorganization of prior experiences; (3) learning is both an individual and social activity, requiring dialogue and cooperation; and (4) learning is context-dependent, with learners reconstructing knowledge to suit specific contexts.

2.3.3.3 Constructivism-Based Teaching Model

Based on the broad principles of constructivism, researchers have proposed many teaching and learning methods. These include Wittrock's generative learning(Wittrock, 1986), Bruner's exploratory learning(Bruner & Studies, 1967), Brown's situational learning(Brown et al., 1989), Barrows' problem-based learning(Barrows & Kelson, 1995), and some teaching models specific to particular fields or subjects, such as CDIO used in engineering education and practice(Moritz & Youn, 2022).

(1) Problem-Based Learning Model

It refers to placing teaching or learning in a poorly structured field of problems that reflect real-world or real-life situations, allowing learners to actively engage as problem solvers. This approach aims to help learners acquire foundational knowledge and basic skills while also fostering their ability for higher-order thinking and problem-solving. In the problem-based learning model, the role of the teacher is to assist learners in acquiring the cognitive skills and collaborative ability needed to solve problems. Learners are the primary actors who analyze problems, gather information, engage in self-directed learning, and participate in group discussions, continually attempting to solve problems. Jonassen(J. F. Johnson et al., 2016) believes that problem-solving is the most common meaningful learning activity. It essentially involves learning through real-life situations or cases, requiring students to use existing subject matter and methods to explore answers to problems. This theory is widely applied in professional fields such as medicine, engineering, and architectural design. Gül et al.(Gül et al., 2008) argue that problem-based, situational, and constructivist learning are essential for effective design education.

(2) Constructionism:

Constructionism, proposed by Seymour Papert (Papert, 1980), is based on the idea that learners construct their knowledge when they build things and share their creations with others. This process is considered the most effective way of learning. Constructionism takes constructivism a step further in an action-oriented direction, emphasizing that learners construct their knowledge by actively designing and creating things. Learning objects play a central role in the learner's knowledge construction. At the same time, constructionism emphasizes the social nature of learning, where both teachers and students can engage in knowledge construction during design and creation activities. Constructionism seamlessly integrates external learning objects with internal knowledge construction during learners' activities.

(3) Experiential Learning (Learning by Doing):

Experiential learning refers to educators carefully and reasonably designing teaching activities and situations to guide students to gain new feelings and understanding of themselves, others, and their surrounding environment through observation, reflection, summarization, and communication during the process of participation. Subsequently, students are encouraged to think, summarize, create, and elevate the knowledge they gain and then apply it to practical life to test it. It is a continuous process of cycling between practice and theory. Experiential learning theory was proposed by American psychologist David Kolb(Kolb, 1983), based on John Dewey's "learning by doing" educational philosophy(Dewey, 1986, 2013). It believes that learning is a process of transforming experience and creating knowledge.

Education is a continuous reconstruction process of experience. Compared with results, it pays more attention to the process. Effective learning starts with experience, followed by reflection, communication, and sharing. The knowledge acquired from this process is then considered in practice, leading to changes in understanding and behavior. Experiential learning theory provides an important theoretical foundation for the cultivation of spatial ability in students. Improving spatial ability requires theoretical guidance, but more importantly, students need to gain conceptual knowledge through experience, observation, reflection, and then use this knowledge to solve real-world problems, testing their knowledge in practice.

(4) Project-Based Learning:

Project-Based Learning (PBL) (Kilpatrick, 1919) is a learning approach guided by constructivism that involves students working in groups to complete project tasks. PBL creates a context for inquiry-based learning, where project problems come from real-life situations. Learners engage in problem-solving, use various tools, and employ specific methods to address the problem. Self-assessment is carried out through an evaluation system, guiding their own learning. During the project, learners not only complete challenging tasks but also construct their own knowledge. The outcomes of learning are generally demonstrated through project results and can reflect the knowledge and skills of the learners. Compared to traditional teaching, PBL advocates for joint decision-making between teachers and students, focusing on skill development and core literacy during the learning process.

(5) Cooperative Learning:

Cooperative learning(Goodman & Abel, 1987) emphasizes students' active participation in learning, problem-solving, and task completion in groups or teams. This educational approach highlights positive interaction, cooperation, and knowledge sharing among students, aiming to cultivate teamwork skills, communication ability, and critical thinking. Here are some key characteristics and principles of cooperative learning:

Small Group Collaboration: Students are typically divided into small groups, each consisting of several members. These groups work together to complete learning tasks, such as problem-solving, project completion, or topic discussion.

Interaction and Communication: Cooperative learning emphasizes active interaction and communication among students. They share their perspectives, raise questions, discuss solutions, and collectively explore learning materials.

Sharing Knowledge: Students not only gain knowledge from teachers but also learn from each other. They share their understanding, help explain complex concepts, and collaboratively build knowledge.

Mutual Support: Cooperative learning encourages mutual support among students. They work together to overcome challenges, provide encouragement, and offer feedback to facilitate successful collaborative learning.

Diversity and Inclusivity: Students in groups may have different backgrounds, skills, and experiences. Cooperative learning respects diversity and considers different viewpoints and experiences as opportunities for learning.

Teacher's Role: In cooperative learning, teachers typically serve as guides and resource providers. They may set tasks, monitor students' progress, and offer necessary support and feedback.

Cooperative learning helps develop students' teamwork skills, problem-solving ability, and critical thinking. It can also increase student engagement and motivation, as many students prefer learning and working together with peers. This educational approach is widely applied in various disciplines and educational levels, contributing to improved learning outcomes and the development of students' social skills.

2.3.4 Blended Course Design Models

Curriculum development theories and models are important concepts in the field of education, serving as guiding frameworks and processes for planning, developing, and implementing educational curricula. Curriculum design models help educators systematically conceptualize, design, develop, implement, and evaluate curricula. They assist in defining the objectives, content, teaching methods, and assessment strategies of the curriculum to ensure that they align with educational goals and provide effective learning experiences. Widely recognized curriculum design models in the field of education include:

(1) ADDIE Model (Linear Model): The ADDIE model is a classic curriculum design model consisting of five stages: Analysis (needs analysis), Design, Development, Implementation, and Evaluation. It is used for curriculum planning and assessment. This model emphasizes continuity and feedback to ensure the quality and adaptability of the curriculum.

Analysis Stage: Determine educational goals, audience needs, and curriculum background.

Design Stage: Develop the curriculum outline, teaching strategies, and assessment methods.

Development Stage: Create curriculum materials, courseware, and educational resources.

Implementation Stage: Implement the curriculum in the classroom or online environment.

Evaluation Stage: Assess the effectiveness of the curriculum, provide feedback, and make improvements.

(2) Bloom's Taxonomy: Bloom's Taxonomy categorizes cognitive objectives into six levels: Remember, Understand, Apply, Analyze, Evaluate, and Create. It assists educators in designing learning objectives and assessment methods at different levels.

(3) Backward Design: The Backward Design model, proposed by Wiggins, emphasizes starting with desired learning outcomes and then designing the curriculum backward to ensure the attainment of educational goals. It involves the clear articulation of ultimate learning objectives, assessment methods, and instructional strategies.

(4) Understanding by Design (UbD): The UbD model, developed by Jay McTighe and Grant Wiggins, places the learner at the center and focuses on problem-solving as the primary content. It promotes diverse assessment of learning outcomes while emphasizing the importance of deep understanding of concepts. It includes six major steps in determining learning goals, designing assessments, and planning instruction.

(5) Project-Based Learning: Project-based learning combines learning with solving real-world problems or completing project tasks, encouraging active participation, problem-solving, and knowledge application by students.

(6) Differentiated Instruction: Differentiated instruction provides personalized education based on students' ability and needs, ensuring that each student can learn at their own level.

(7) Task-Based Learning: Task-based learning focuses on students completing real tasks, emphasizing problem-solving and practical application skills, where students need to solve specific problems to acquire knowledge and skills.

(8) Situated Learning: Situated learning places learning within specific contexts or backgrounds to increase relevance and practicality. John Dewey's situated

curriculum design emphasizes putting learning in real-life contexts, enabling students to apply acquired knowledge and skills.

(9) Self-Directed Learning: Self-directed learning encourages students to take more responsibility for their learning process, enhancing self-directed learning and problem-solving skills.

(10) Collaborative Learning: Collaborative learning emphasizes students working together in groups to solve problems, fostering teamwork and communication skills.

(11) Multimodal Course Design: Multimodal teaching recognizes that students have different learning styles and needs, so curricula should use various teaching methods and resources to meet diverse student needs.

(12) Reflective Course Design: Schön's reflective educational model emphasizes cultivating students' reflection and metacognitive ability to improve learning outcomes.

(13) Problem-Centered Course Design: Barrows' problem-centered instructional design model focuses on problem-centered learning, encouraging students' inquiry, questioning, and problem-solving skills, emphasizing student autonomy.

(14) Personalized Learning: Personalized learning models focus on tailoring curricula to individual students' needs and learning styles to meet unique student needs.

(15) Spiral Curriculum: The spiral curriculum emphasizes repetitive learning and progression, with students gradually deepening their understanding as they revisit the same topic multiple times. Each round of learning centers around the same theme but increases in depth.

(16) Constructivist Course Design: Piaget's constructivist theory posits that learning is an individual process of constructing knowledge. Prust's constructivist-based curriculum development model emphasizes active student engagement, social interaction, and real experiences.

These curriculum development models offer different approaches and strategies to meet various educational needs and goals. Curriculum designers can select the appropriate model to guide curriculum development and implementation based on specific circumstances. These theories and models can be flexibly adjusted and combined to suit different educational goals, student needs, subject areas, and educational environments.

Since 2015, the “EDUCAUSE Horizon Report: Teaching and Learning Edition” has consistently emphasized that blended learning is a core trend for advancing the application of educational technology in higher education(Pelletier et al., 2022). In the book "The Handbook of Blended Learning", Bonk & Graham(2012) points out that blended learning is a revolution in 21st-century learning, fostering the development of K-12 education. Through years of research and teaching practice, numerous blended learning project cases are listed With the continuous advancement of educational technology and pedagogy, blended learning has been evolving and gaining popularity. The COVID-19 pandemic in 2020 accelerated the adoption of blended learning, as schools and institutions sought ways to provide remote and flexible learning options. Many schools and universities have formally integrated blended learning into their curriculum design, and educators have developed various models and strategies for its effective implementation.

Blended course design models involve combining different curriculum design models and methods to create a blended approach that meets specific educational needs and goals. This blend typically involves integrating traditional face-to-face teaching and online learning resources to provide a more flexible, diverse, and effective learning experience. This flexible approach to course design allows educators to customize instruction based on specific disciplines, student populations, and educational objectives. The flexibility of blended course design accommodates diverse educational needs and encourages deeper student engagement and understanding. Designing a successful blended course model requires considering multiple factors, including educational objectives, student needs, instructional resources, technology tools, and assessment methods. Here is a general overview of the blended course model design process:

Clarify Educational Objectives: Start by defining the educational objectives and learning outcomes of the course. These objectives should be clear, specific, measurable, and aligned with the course's content and assessment methods.

Analyze Student Needs: Understand students' backgrounds, learning styles, technological competencies, and time availability to determine how best to meet their needs.

Select a Blended Model: Based on educational objectives and student needs, choose an appropriate blended model. Common blended models include flipped classrooms, rotation models, and deep-blend models, among others.

Design Online Learning Components: Develop online learning materials, including video lectures, online modules, discussion forums, online quizzes, etc. Ensure that these resources align with the course objectives and effectively support student learning.

Integrate Face-to-Face and Online Learning: Determine which course content is suitable for online learning and which is best delivered in face-to-face instruction. Establish a clear schedule for integrating both modes.

Choose Technology Tools: Select suitable technology tools and a learning management system (LMS) to support the online learning components. Ensure that students can access and use these tools conveniently.

Implement the Blended Course: Implement the blended course, ensuring that students understand the course structure and learning activities. Provide support and guidance to help students adapt to the blended learning environment.

Assess Student Learning: Use a variety of assessment methods to evaluate student learning outcomes, including online quizzes, assignments, projects, class participation, etc. Ensure that assessments align with the educational objectives.

Provide Feedback and Improvement: Collect student feedback and course data to make improvements based on feedback and data. Continuously optimize the quality and effectiveness of the blended course.

Evaluate Overall Effectiveness: Finally, assess the overall effectiveness of the blended course, including student learning outcomes, satisfaction, and the extent to which course objectives are met. Make further improvements based on the evaluation results.

The design of a blended course model is a dynamic process that requires ongoing adjustment and improvement to meet the needs of students and educational goals. Designers must pay attention to the alignment of educational objectives, student engagement, technology tools, and assessment methods to ensure the successful implementation of a blended course.

2.4 3DMP and Spatial Ability

2.4.1 3D Modeling

3D modeling refers to the process of creating three-dimensional objects or scenes in a computer environment. It is a digital method used for designing, simulating, and visualizing the three-dimensional shape and appearance of objects. Three-dimensional modeling finds widespread applications in various fields, including computer graphics, animation production, engineering design, architectural planning, medical imaging, game development, and virtual reality, among others.

Three-dimensional modeling typically involves the following steps: (1) Conceptual Design: Firstly, designers or artists determine the concept or outline of the desired three-dimensional model. This may involve hand-drawn sketches or textual descriptions. (2) Modeling: Using specialized 3D modeling software on a computer, the concept is transformed into a specific three-dimensional model. Modeling can be done manually by creating models through drawing, stretching, scaling, and rotating basic geometric shapes, or it can involve scanning real-world objects and converting them into digital models. (3) Materials and Textures: Materials and textures are applied to the model to give it its appearance and surface characteristics. This may include coloring the model, adding texture images, or simulating the reflection and gloss of materials. (4) Lighting and Rendering: Designers can add virtual light sources to the scene or model to simulate lighting effects. Then, they use a rendering engine to generate the final images or animations, taking into account lighting, shadows, reflections, and refractions, among other effects. (5) Animation (Optional): If necessary, three-dimensional models can be animated to create dynamic effects. This is very common in film production, game development, and virtual reality. (6) Export and Application: The completed three-dimensional model can be exported to various file formats and used in various applications, such as video game engines, virtual reality devices, architectural design software, and more.

The basic geometric elements of a three-dimensional model include points, lines, and faces. A point is a unique location in geometric space within a coordinate system, and two points can define a line, while three points or three lines can define a two-dimensional plane. A three-dimensional model is a geometric representation of a physical object that is complete and well-defined. Three-dimensional modeling (based on 3D CAD) primarily employs three methods. The first method involves combining basic geometric entities through Boolean operations such as union, subtraction, and intersection to create more complex three-dimensional solid models. Basic geometric entities include cubes, cylinders (circular and prismatic), spheres, cones (circular and prismatic), wedges, and tori. The second method involves editing basic geometric solid models using solid geometric features to generate three-dimensional solid models. Solid geometric features are divided into basic features (e.g., extrusion, rotation, sweeping, blending) and engineering features (e.g., holes, shells, ribs, drafts, and chamfers). The third method, sketch-based modeling, is the most commonly used approach. It combines aspects of the first two methods and allows for the creation of more detailed solid geometric features to generate three-dimensional models.

In some cases, three-dimensional modeling may be replaced or combined with 3D CAD. While they are closely related, there are some differences between the two. The biggest difference lies in their purpose and focus. Three-dimensional modeling is more general and emphasizes creating various three-dimensional models in fields like art, animation, and virtual reality. On the other hand, 3D CAD is more specialized for engineering and design applications, primarily used for designing and modeling mechanical parts, architectural structures, circuit boards, automotive components, and more, for precise engineering design and manufacturing. 3D CAD software typically offers features specific to engineering design. In contrast, 3D modeling software may prioritize artistic and creative tools, such as sculpting and animation. 3D CAD places a strong emphasis on accuracy and measurements, whereas in some three-dimensional modeling applications, precision may not be the primary focus, with greater emphasis on creativity and visual effects.

Three-dimensional modeling has become an important component of today's educational system, helping students better adapt to the demands of the modern society and workplace. Three-dimensional modeling courses are widely recognized in modern society and across multiple fields for the following reasons: (1) Meeting the Needs of Various Industries: Three-dimensional modeling is an essential skill in industries such as engineering, architecture, manufacturing, film production, game development, and virtual reality. Learning three-dimensional modeling enables students to meet the demand for professionals with these skills in these industries. (2) Innovation and Design: Three-dimensional modeling is a key tool in the innovation and design process. It allows designers and engineers to create, modify, and test products and design concepts in virtual environments, saving time and resources while enhancing creativity. (3) Experimentation and Simulation: Three-dimensional modeling can be used to create virtual experiments and simulation environments. This is highly valuable in fields such as medicine, scientific research, and flight simulation because it allows students to engage in practical exercises without the need for real equipment or risks. (4) Virtual Reality and Augmented Reality: Three-dimensional modeling serves as the foundation for virtual reality (VR) and augmented reality (AR) applications. Learning three-dimensional modeling equips students with the skills to create virtual worlds and AR applications, which have significant potential in areas like game development, training, and entertainment. (5) Educational Value: Three-dimensional modeling can make education more engaging and interactive. It can be used to create educational games, virtual laboratories, interactive course content, educational tool modeling, and more, helping to enhance student interest and engagement. (6) Problem Solving and Creativity: Learning three-dimensional modeling fosters students' problem-solving ability and creativity. They can tackle various challenges, such as designing new products, solving engineering problems, or creating complex virtual environments.

2.4.2 3D Printing

3D printing is a rapid prototyping technology, also known as Additive Manufacturing (AM). It allows objects to be created in three dimensions by layering or adding material, making it more flexible and resource-efficient compared to traditional subtractive manufacturing methods like cutting and casting. The history of 3D printing can be traced back to the 1980s and 1990s when the technology was still in the experimental and early prototype stages. Over the decades, 3D printing has undergone development and evolution, progressing from initial laboratory concepts to today's commercial applications. It has revolutionized the way manufacturing and innovation are approached, providing new solutions for custom manufacturing, prototyping, and small-batch production, with the potential to expand into more fields in the future. As technology continues to advance, 3D printing is expected to play a larger role in global industries.

The 3D printing process, as shown in Figure 6, typically includes the following steps: (1) Slicing: The designed 3D model is sliced into multiple thin layers, creating a digital hierarchy. (2) Printing: A 3D printer constructs the object by adding material layer by layer based on the information from each slice. Various technologies such as lasers, nozzles, UV curing, and others are used to achieve this layer-by-layer process. (3) Post-processing: After printing is completed, some post-processing may be required, such as removing support structures, smoothing the surface, coloring, etc., to meet the desired quality standards for the printed object.

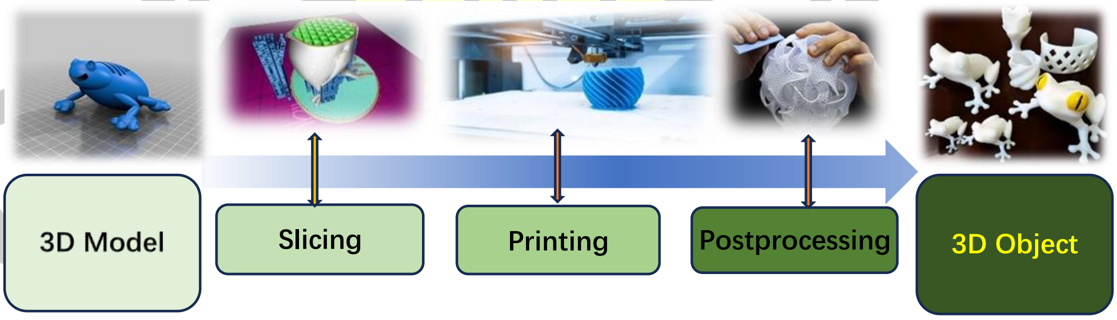


Figure 6 3D Printing Workflow Diagram

3D printing technology offers several advantages, including: (1) Customization: It allows the creation of personalized objects tailored to specific needs. (2) Rapid Prototyping: It enables the quick production of prototypes for testing and validation.

(3) Resource Efficiency: Compared to traditional manufacturing methods, it reduces waste generation. (4) Complex Structures: It can manufacture objects with intricate geometric shapes that are challenging to produce using conventional methods.

3D printing technology finds extensive applications across various fields, including but not limited to: (1) Manufacturing: Used for prototyping, custom component manufacturing, tool production, and more. (2) Healthcare: Employed to create custom medical devices, prosthetics, dental aligners, and more. (3) Aerospace: Utilized for manufacturing lightweight components and prototypes, reducing aircraft weight. (4) Automotive Industry: Applied in the production of automotive parts and customized accessories. (5) Construction: Used for manufacturing architectural prototypes, models, and exterior architectural elements. (6) Arts and Culture: Artists use 3D printing to create sculptures, artworks, and more. (7) Education: Integrated into educational settings for teaching and hands-on learning.

Fused Deposition Modeling (FDM) is a popular 3D printing technology that uses a thermoplastic filament as the printing material. FDM 3D printers are widely used for their affordability, ease of use, and versatility. Here's how FDM works: (1) Material Feed: A solid, filament-shaped material, typically made of thermoplastic, is fed into the 3D printer. (2) Heating: The printer's print head, also known as an extruder, heats the filament to its melting point. This makes the material soft and malleable. (3) Layer-by-Layer Deposition: The melted material is extruded onto the build platform or the previous layer of the object being printed. The printer deposits the material in thin layers, typically ranging from 0.1 to 0.3 millimeters in thickness. (4) Solidification: As the extruded material is deposited, it quickly cools and solidifies. This process is repeated layer by layer until the entire 3D object is built. (5) Support Structures (if needed): In some cases, support structures made of the same or a different material may be printed alongside the object to provide stability during printing. These supports can be removed after the print is complete. （6）Completion:

Once all the layers have been deposited and the 3D object is fully formed, it can be removed from the build platform.

The rise and application of 3D printing technology in the education industry have garnered widespread attention because it provides students with opportunities for innovative, hands-on, and interdisciplinary learning. Here are the ways in which 3D printing has risen and been applied in the field of education:

(1) Support for STEM Education: 3D printing is extensively used to support Science, Technology, Engineering, and Mathematics (STEM) education. Students can use 3D printers to create models, prototypes, and experimental equipment, helping them better understand complex scientific and engineering concepts.

(2) Interdisciplinary Projects: 3D printing encourages interdisciplinary projects, helping students integrate knowledge from different disciplines to solve complex problems. For example, 3D printing is used to create models, prototypes, and experimental equipment, aiding in science and engineering education. Students can fabricate and test their designs, deepening their understanding of scientific principles. They can also write computer programs to control 3D printers, thereby learning programming and automation skills, promoting computer science education. 3D printing provides a creative medium for art and design students, allowing them to create artworks, sculptures, and custom design projects.

(3) Innovative Educational Tools: 3D printing technology offers an innovative educational tool that helps students better grasp abstract concepts by enhancing learning experiences through hands-on object creation. This practical educational approach enhances the depth and retention of learning. Educators can use 3D printing to create custom educational resources, such as replicas of historical artifacts to help students better understand historical events and geographic concepts. These models can be used for teaching and display. 3D printing can be used to create biology

models, human organ models, and molecular structure models, supporting education and research in the fields of medicine and life sciences.

(4) Personalized Learning and Growth: 3D printing allows educators to create personalized educational resources based on students' needs and interests. Students can choose and design projects they are interested in, increasing their engagement in learning. 3D printing sparks students' interest in fields such as science, engineering, design, and art. Students are more likely to be engaged in learning because they can personally create interesting projects. Additionally, 3D printing technology is widely used in many industries, allowing students to acquire skills needed for future careers through learning this technology.

(5) Collaborative Learning and Sharing: The use and application of 3D printing involve multiple disciplines and fields, requiring collaboration among different subject teams or groups to complete interdisciplinary projects. Moreover, many 3D printer projects are open source, and there are many corresponding resource-sharing platforms online. 3D printing technology enables students to participate in global collaborative projects, work together with other students to solve problems, and share designs. This helps cultivate global awareness and teamwork skills.

2.4.3 Integration and Application of 3DMP Courses

Three-dimensional modeling is the process of creating virtual three-dimensional models, conducted on computers, primarily used for design and visualization. 3D printing is the process of transforming virtual three-dimensional models into physical objects, involving the stacking and manufacturing of physical materials. Three-dimensional modeling is typically the first step in creating objects for 3D printing. Before 3D printing, a virtual three-dimensional model must first be created. This model can be designed and edited by designers using three-dimensional modeling software. Three-dimensional modeling and 3D printing are complementary technologies that together promote improvements in the innovation and manufacturing processes. Modelers can use three-dimensional modeling software to create designs, which can then be sent to a 3D printer for the production of physical objects. This combination makes the process from creativity to the creation of physical objects easier and faster. Prior to 3D printing, slicing programs are required, which are implemented using computer slicing software, and the operation of 3D printers is also controlled by a series of computational programs. Therefore, three-dimensional modeling and 3D printing can be collectively referred to as computer-based activities or the application of computer technology in training, with 3D printing being an extension and extension of three-dimensional modeling into the physical world.

2.4.3.1 3DMP and Spatial Cognition

In the field of education, specifically in enhancing students' spatial ability, 3DMP serves as both an educational tool and method. In education, 3DMP acts as a cognitive tool to strengthen the construction of students' spatial concepts and enhance spatial ability. In subject-specific education, the integration of 3DMP into curriculum teaching may become an effective means to improve spatial ability and subject learning(Suzuki, 2018; Turğut, 2016).

Piaget(1956)proposed that physical, hands-on activities are crucial for children to develop spatial thinking. Piaget et al (Piaget, 1974; Piaget & Inhelder, 1956) discovered that spatial ability, aside from developing with age, also significantly depend on children's practical hands-on experience. In many educational research studies involving the application of 3DMP, the learning tasks inherently involve spatial cognitive activities designed for hands-on student engagement. For example, in STEM interdisciplinary education research, Oi-Lam Ng and Chan (Ng & Chan, 2018) designed learning tasks for primary school students (aged 10-11) and middle school students (aged 12-13) that integrated 3D CAD to enhance mathematical and spatial learning. In these learning tasks, which involved making keychains and creating castles, students used 3D CAD for tasks such as measuring and calculating the volume of composite entities, decomposing and composing two-dimensional shapes, and integrating various STEM learning practices. The research results showed that spatial cognitive activities supported by 3D CAD not only facilitated productive interdisciplinary STEM learning experiences but also significantly surpassed traditional subject teaching methods based on mathematical formula derivation and calculation in cultivating students' spatial ability and mathematical learning.

From Piaget's theory(Piaget & Inhelder, 1956) of childhood spatial cognitive development and related research, we can conclude two relevant points for this study. First, improvement in spatial ability occurs across different age stages, and at any given stage, there are considerable individual differences in spatial ability. All types of spatial ability are continuously developing and becoming increasingly integrated. Second, spatial cognitive activities contribute to the acquisition of spatial thinking. Therefore, to enhance students' spatial ability, the design of 3D CAD courses can create teaching and learning contexts with enhanced spatial cognitive activities and require the selection of appropriate spatial cognitive activities based on cognitive development levels.

2.4.3.2 3DMP and Multimodality

3DMP involves the use of computer software (3D CAD, slicing software, etc.) with Graphical User Interface (GUI) that employ standard WIMP (Windows, Icons, Menus, Pointers) principles. Interaction is achieved through input/output devices such as keyboards, mice, drawing tablets, and computer screens. This implies that the interaction in 3D CAD regarding modeling and assembly visualization is not always efficient or intuitive, as the three-dimensional modeling space must be mapped onto two-dimensional space on input/output devices. Users need to distinguish between the two-dimensional space of input/output devices and the three-dimensional modeling space and should be capable of switching between them. This convenient and practical human-computer interaction method involves spatial cognitive activities and hands-on experience, which can contribute to cultivating students' spatial ability.

Three-dimensional modeling is a core component of modern graphics education courses. It fully utilizes three-dimensional spatial feature information (visual spatial elements such as size, shape, and orientation) to achieve a three-dimensional visual experience, optimize visual spatial cognitive load, and enhance visual representation capability. In three-dimensional design and production, teachers can simultaneously present two-dimensional plan views and three-dimensional physical models. This allows for a detailed analysis of the drawing concepts and drawing steps for three-dimensional physical models and their corresponding two-dimensional plan views. Students can use multi-view drawings and physical models, select their preferred modes, imagine the external appearance, internal structure, and cross-sectional contour shapes of artificial products they want to create, and obtain spatial feature information for spatial description. This assists them in accurately representing, drawing, and editing the cross-sectional contour shapes and geometric features of the artificial products they intend to create. Curriculum design research on improving spatial ability has demonstrated that creating three-dimensional solid models using 3D CAD can help enhance spatial cognitive processing ability(Carroll, 1993; Mart ́n-Dorta et al., 2008). In the field of biology education, interactive three-dimensional solid models significantly enhance students' construction of scientifically grounded visual representations when learning about biological cells. Meanwhile, research has found that students with low spatial ability experience cognitive overload, whereas those with high spatial ability experience reduced cognitive load and perform better in solving discipline-related problems regarding cells(Barrett & Hegarty, 2016; Huk, 2006). In mathematics education, experiments have shown that in dynamic geometry environments (DGEs), teaching with three-dimensional geometric transformations (such as reflection and rotation) significantly enhances students' spatial imagination. Additionally, high-spatial-ability students outperform medium-spatial-ability students, who, in turn, outperform low-spatial-ability students in solving geometry-related problems(Dixon, 1995; Moses, 1977).

The use of multiple representational modalities is aimed at enhancing people's cognitive ability for conveying and processing visual and spatial information. Visualization techniques and tools for the mental representation process can range from simple pen-and-paper tools to complex high-performance computing systems. Common tools and techniques that support visual-spatial thinking include paper drawings, maps, models made from lightweight wood or cardboard, compasses, GPS devices, CAD systems, and virtual reality, among others. The choice of technology and tools typically depends on practical needs rather than pursuing the advancedness of technology and tools. The application of 3DMP systems provides visual-spatial cognitive thinking activities that promote the use of multiple representational modalities or, in other words, supports the use of multiple representational modalities to solve real-world problems that involve visual object recognition and spatial relationship representation. As mentioned earlier, during the initial stages of mechanical and product design, freehand drawing of multi-view drawings, which is fast but less precise, can be chosen to convey and process vague and unformed ideas. However, when drawing complex geometric shapes or making repeated modifications, clearer, more explicit, and more operational 3DMP can be used to think about and solve problems, effectively assisting in more advanced visual-spatial cognitive thinking activities(Keehner et al., 2008; Korakakis et al., 2009). In summary, within the context of 3DMP system applications, visual-spatial cognitive activities involving multiple representational modalities mainly include spatial description, gestures, multi-view drawing, three-dimensional solid modeling, and physical production, all of which can support the enhancement of spatial ability(Suzuki, 2018). Table 4 describes these visual-spatial cognitive activities and their corresponding representational modalities.

Table 4 3DMP Spatial Cognitive Activities and Corresponding Modalities

Activity	Modality	Representational Modality	Sensory Organs / Media
Spatial Description	Language, physical models, images, videos, or other symbolic systems	Visual representation, symbolic modality	Mouth, ears, eyes, hands / paper, maps, compasses, GPS, graphics software, display, mouse, keyboard
Gestures	Rhythmic gestures	Visual representation, kinesthetic modality	Hands, eyes
	Expressive gestures	Visual representation, symbolic modality, kinesthetic modality	
Multi-View Drawing	Line drawings, annotated text, multi-view drawing and reading	Symbolic modality, visual representation, kinesthetic modality	Hands, eyes / pen, paper, CAD software
3D Modeling	Geometric modeling; Geometric features	Symbolic modality, visual representation	Hands, eyes / pen, paper, CAD software, display, mouse, keyboard
	Geometric feature editing; Virtual assembly	Visual representation, kinesthetic modality	Hands, eyes / CAD software, display, mouse, keyboard
Physical Fabrication	3D printing materials and instrument	Symbolic modality, visual representation, kinesthetic modalit	Hands, eyes / slicing software, display, mouse, keyboard, 3D printer

In the process of comprehensive social informatization, the use of multimodal approaches in daily life, work, and learning has become commonplace. Based on multimodal theory, this study's 3DMP course integrates various representational modalities, such as 3D CAD applications and 3D printing, effectively promoting the enhancement of students' spatial ability with the aim of achieving the desired teaching outcomes. Specifically, the core content of the 3D CAD course is to enable students to use 3D CAD to design and create three-dimensional solid models for artificial products. In the modeling process， symbolic Modality is used to help students read or draw multi-view drawings, allowing them to use mathematical and engineering terminology to describe the external appearance and internal structure of the artificial product to be created. Visual Representation allows students to imagine the cross-sectional contour shapes and geometric features required to create the three-dimensional solid model using 3D CAD, based on multi-view drawings. Kinesthetic Modality enables students to proficiently operate 3D CAD tools used to create three-dimensional solid models. This includes dynamically transforming two-dimensional and three-dimensional views using navigation tools, observing three-dimensional solids from different angles, using sketching tools to draw and edit the cross-sectional contour shapes of the artificial product to be created, and employing geometric feature editing tools to generate three-dimensional solid models. To achieve effective teaching, it is necessary to create 3D CAD technologies and services that support various representational modalities and develop course resources in various modalities, such as physical models, engineering drawings, documents, and micro-videos. 3D printing not only provides physical models for three-dimensional modeling but also represents a multimodal process in teaching and using 3D printing technology.

2.4.3.3 3DMP and Constructivism

Learning with 3DMP involves interpretation, analysis, discovery, evaluation, action, and problem-solving, which shares similarities with the constructivist view that knowledge is actively constructed by learners as they analyze and solve problems in specific contexts. Three-dimensional modeling (3DMP) is a part of virtual simulation used to create objects and scenes in a virtual world. From a simulation perspective, 3D printing is also a form of simulation creation, as 3D printed objects can, under certain circumstances, simulate real-world physical objects. Dalgarno(Dalgarno, 1999) applied Moshman (1986)'s three constructivist (Intrinsic Constructivism, Extrinsic Constructivism, and Dialectical Constructivism) viewpoints to discuss the relevant theories and technologies of constructivist computer-assisted learning. This section will draw from some of these viewpoints and provide insights into the potential value of 3DMP as a constructivist learning environment.

(1) 3DMP and Internal Constructivism

Internal constructivism emphasizes learners' active engagement in the process of knowledge discovery, which, for 3DMP, includes simulating observable aspects of the real world and abstract conceptual simulations. Internal constructivism underscores that learners acquire knowledge through interaction with their environment, rather than direct instruction (instructive teaching). This approach provides learners with real contexts for exploration and experimentation, allowing them to construct their own mental models of the environment. When concepts, whether concrete or abstract, are presented in three-dimensional form, the application of 3D simulation becomes particularly appropriate. It is suggested that exploring three-dimensional representations on a two-dimensional screen helps learners form hypotheses about three-dimensional mental models(Rieber, 1992). Dalgarno(Dalgarno, 2002) also argues that any knowledge domain where an understanding of entities with dynamic behaviors is required is suitable for highly interactive simulations. 3DMP can support the examination of design concepts, reasoning, and various other important cognitive skills. Students, when creating design concepts, construct relevant domain knowledge, especially when they have creative ideas and are willing to put in more effort to optimize their designs and generate more creative ideas.

(2) 3DMP and External Constructivism

External constructivist interpretations of constructivism emphasize the role of direct instruction. Activities conducted in 3D virtual environments that can simulate parts of the knowledge domain can help learners develop their own conceptual models based on what they have learned. This type of 3DMP, consistent with external interpretations, can receive support from traditional learning resources. In other words, when learners explore and implement tasks in a 3DMP environment, they can access conventional teaching resources, such as text, graphics, and videos. This can allow for greater control over activity selection and sequence through more extensive system control. External constructivist interpretations also emphasize the use of cognitive tools that can enhance learners' understanding. As constructivism highlights the importance of individual knowledge construction, the use of metacognitive strategies can improve learners' understanding, memory, and individual knowledge construction. These strategies are particularly important for external constructivism. It is advocated that these strategies can be directly taught to students, and computer-based cognitive tools can assist in these strategies. According to Jonassen(Jonassen, 2003), such tools expand students' thinking and facilitate knowledge construction, while Wild(Wild & Kirkpatrick, 1996) suggest that these tools (text tools, concept mapping tools, and modeling tools, among others) can provide learners with ways to construct, manipulate, and evaluate knowledge representations. If using three-dimensional mental models can help learners better understand explored or articulated concepts, whether concrete or abstract, or visualized data in three components, then three-dimensional concept maps or three-dimensional graphical tools may be more appropriate than two-dimensional tools.

(3) 3DMP and Dialectical Constructivism

Dialectical constructivist interpretations emphasize that real activity is supported by learners and peers, experts, or teachers, or that learning activities are carried out with scaffolding. Learners collaborate in learning and enhance their understanding of concepts through social learning processes. Dialectical constructivist interpretations emphasize that real activity is supported by learners and peers, experts, or teachers, or that learning activities are carried out with scaffolding. Learners collaborate in learning and enhance their understanding of concepts through social learning processes.

2.4.4 Development of 3DMP for Improving Spatial Ability

2.4.4.1 Overview of research on 3DMP to improve spatial ability

Three-dimensional modeling and 3D printing have not only made a significant impact on manufacturing and technology industries but have also found numerous applications in the field of education. Irwin(Irwin et al., 2015) believes that 3D printing technology has a significant role to play in STEM education, allowing students to explore 3D printing in STEM classrooms, such as in part manufacturing and model creation. As 3D printing technology matures, various countries have formulated policies related to 3D printing education and invested significant funds in this area. In the UK, a 3D printing education pilot project was conducted in 2012-2013, attempting to integrate 3D printing with STEM subjects. The UK Department of Education has also initiated a series of research projects focusing on the development of 3D printing technology and its integration with STEM education to drive innovation in educational practices. Starting from 2015, Japan and South Korea have conducted pilot 3D printing courses in their middle schools. The U.S. government has adopted a comprehensive approach to train young people in 3D printing innovation awareness and modeling techniques to promote the country's manufacturing industry and apply 3D printing in projects such as robotics competitions and creative construction, enabling students to acquire practical skills. In 2020, Think Huts organization in the United States announced plans to establish the world's first 3D printing school, and in 2021, Anglia Ruskin University unveiled a graduate degree program in 3D printing. 3D printing technology has been widely adopted in the education sector in European and American countries, serving as a powerful means to advance STEM education. Many classrooms in the United States have introduced 3D printers as essential teaching tools and methods. Professor Gran. Boole of the University of Virginia stated that they have been dedicated to researching the educational applications of 3D printing, hoping to cultivate spatial ability in students of preschool age through advanced equipment and theoretical knowledge. He expressed his desire for 3D printing courses to be available in classrooms across the United States. In China, inspired by Western countries like the United States, research on the use of 3D printing in education has gained momentum. Many primary and secondary schools, especially in major cities like Beijing, Shanghai, and Guangzhou, have equipped themselves with 3D printers and established innovation laboratories. 3D printing has found its way into classrooms in various forms, including extracurricular clubs and competitions.

By collecting, organizing, categorizing, and analyzing relevant literature (for specific methods, refer to Chapter 3, Section 1), research literature on the enhancement of spatial ability through 3DMP can be divided into two categories: technological advancements for improving spatial ability and teaching methods for enhancing spatial ability. The following examples illustrate each category.

2.4.4.2 Technological Advancements for Improving Spatial Ability

This section of the literature aims to explore whether 3D printing technology or 3D modeling software can enhance students' spatial ability.

Šafhalter (Šafhalter et al., 2014) conducted a study involving 196 students from 11 middle schools, dividing them into an experimental group (95 students) and a control group (101 students). The experimental group participated in extracurricular 3D modeling activities using SketchUp, while the control group did not. This 3D modeling extracurricular activity spanned two semesters. Based on existing spatial ability scales, the researchers developed their own Mixed Spatial Ability Tests 1 and 2 and conducted pre- and post-tests on the study subjects. The conclusion was that three-dimensional modeling had a positive impact on the spatial ability of middle school students aged 11-15, with greater improvements seen among females, though the overall growth in spatial ability did not show significant differences.

Toptaş (Toptaş et al., 2012) selected 82 eighth-grade students as their subjects to investigate (1) whether eighth-grade students using SketchUp for learning differed in spatial imagination from those who did not use any modeling software and (2) how gender differences affected eighth-grade students' spatial imagination. Following Linn (Linn & Petersen, 1985) 's classification of spatial ability (spatial perception, mental rotation, and spatial imagination), the researchers used the MRT, Differential Aptitude Test - Spatial Relations (DAT), and Spatial Visualization Test (SVT) as research tools. The study subjects were divided into an experimental group (42 individuals) and a control group (40 individuals), with the experimental group receiving six weeks of SketchUp instruction (60 to 80 minutes per week). The results showed that (1) the use of dynamic geometry tools had an impact on the development of learners' spatial ability, even if they had never used such tools before; (2) cooperative learning improved students' overall spatial learning, but significant results required increased time and repeated experiments; (3) regardless of the literature reviewed, in this study, female students performed better in spatial visualization compared to male students.

In another study, Sun et al (Sun et al., 2016) conducted research with 48 students from a high school in Shanghai, China. Among them, 24 were in the experimental group, and 24 were in the control group. The researchers integrated a 3D printing and creative design school-based curriculum into the experimental group's education over four weeks, totaling 8 class hours. They used the Purdue Spatial Visualization Test-Visualization of Rotations (PSVT: R) and the Williams Creativity Test to conduct pre- and post-tests on the subjects' spatial ability and creativity. The results indicated that computer-aided design learning in three dimensions could enhance learners' spatial ability, and there was a positive correlation between spatial ability and creativity. Additionally, the study found gender differences in the impact of three-dimensional computer-aided design on learners' spatial ability and creativity.

Kornkasem and Black(Kornkasem & Black, 2015) explored the effects of different training methods on the spatial ability of 115 Columbia University students. The researcher designed three experiments. In the first experiment, with 48 participants, the subjects were divided into experimental and control groups. They engaged in teaching activities lasting two days and lasting 50 minutes each day in a 3D virtual environment (SketchUp) and a 3D physical environment (building blocks). The activities included introducing the learning environment, having learners draw views of seven given stimuli, requiring learners to rotate objects in different directions as instructed, and having learners solve problems. The conclusion was that all participants showed improvement in the post-test, with a significant difference between the 3D virtual environment group and the 3D physical environment group. The researcher identified some issues in Experiment 1 and improved upon them in Experiment 2. These improvements included addressing issues related to computer-user interaction, eliminating teaching activity 2 (to determine whether the improvement in learners' ability was due to drawing or rotating activities), and adjusting and modifying the scale. In Experiment 2, with 28 participants, the independent variable was the 3D modeling software that could be operated via touch screen (SketchUp) and the 3D physical environment (building blocks). The subjects participated in teaching activities lasting two days, with 50 minutes each day. The research concluded that the improvement was more pronounced in the 3D virtual group than in the 3D physical group. Experiment 3 involved 39 participants divided into 3D virtual environment and 3D physical environment groups. Members of both groups were randomly divided into two categories: Category A had the freedom to manipulate objects, while Category B had to write down the input rotation angles and quantities before manipulating the objects. There was no time limit for practice in both groups. The conclusion was that all participants showed improvement in the post-test, but there was no significant difference between Category B members of the 3D virtual environment group and the 3D physical environment group.

2.4.4.3 Teaching Methods to Enhance Spatial Ability

This section of the literature aims to explore whether certain teaching methods can improve students' spatial ability.

For instance, Chang(Chang, 2014) conducted a study with 349 senior high school students in Taoyuan County, Taiwan. The students were randomly divided into an experimental group and a control group. The experiment had two independent variables: teaching strategies (the experimental group received 20 hours of 3D modeling instruction, while the control group received traditional classroom instruction) and spatial ability. The dependent variable was creative performance, measured using a creative performance assessment scale. This study utilized a non-equivalent pretest-posttest quasi-experimental design, with pretest scores based on designs created before instruction and spatial ability test scores. The unit task involved designing a multi-purpose pencil holder, and the assessment of this design served as the posttest score. Through data analysis, the results indicated that (1) students' spatial ability were moderately correlated with their creative performance, particularly in the functional dimension; (2) 3D-CAD applications improved students' creative performance, especially in the aesthetic dimension; (3) in the context of 3D-CAD applications, students with higher spatial ability outperformed those with lower spatial ability in terms of creative performance. Furthermore, the effects of novelty and aesthetics were greater than that of functionality. Additionally, the study found that students with better spatial ability tended to apply analytical thinking to the design of objects, while those with weaker spatial ability tended to view designed objects as a whole or even as images, making it difficult for them to perform 3D rotations and manipulations.

Martín-Dorta (Mart ń-Dorta et al., 2008)found that in current Spanish university courses for civil engineering majors, there is a decreasing emphasis on teaching topics related to engineering design graphics. Due to varying levels of incoming student proficiency, some students face challenges in developing their spatial ability. Therefore, the researcher developed a rapid spatial ability improvement course targeting first-year civil engineering students with weak spatial ability. The goal was to help these students reach the minimum required spatial ability level for the major, facilitating their participation in the regular engineering drafting course in the first semester. The study involved 40 self-identified students with weak spatial ability and lasted three weeks (a total of 12 hours). This research considered spatial ability as comprising spatial relations and spatial imagination and used the Meatal Rotation Test (MRT) and the Differential Aptitude Test - Spatial Relations Subset (DAT: SR) scale for pre- and post-tests. The results showed that spatial ability can be improved through training, and the effectiveness of the rapid improvement course designed in this study was confirmed.

Huang (Huang & Lin, 2017) from National Taichung University of Science and Technology applied the CDIO (Conceive, Design, Implement, Operate) educational framework to a 3D printing course for university students. This course combined 3D printing with physical materials and involved 13 university students in a four-week (36-hour) teaching program. Pretest, mid-test, and post-test assessments of psychological rotation and spatial imagination were conducted using the MRT and PSVT scales. Data analysis confirmed the improvement of students' spatial ability. This study developed a CDIO-integrated three-dimensional modeling teaching model to explore learners' spatial ability. Additionally, the research found that tasks of lower difficulty required learners to use visual aids such as three-view drawings, while tasks of higher complexity required learners to use both three-view drawings and physical models to enhance learning effectiveness.

2.4.5 Challenges of Improving Spatial Ability with 3DMP

Research on spatial ability is an interdisciplinary field that involves multiple disciplines such as psychology, education, geography, neuroscience, engineering, and more. Research on spatial ability is continually evolving and expanding, involving various fields and stakeholders. Advancements in this field contribute to improvements in education, navigation technology, healthcare, and various other applications, providing people with enhanced spatial cognition and navigation skills. The study of spatial ability in the field of education has received significant attention and serves as a key cognitive ability predictor for career selection. This is because it is closely related to students' academic performance and problem-solving skills and can influence their choice of careers in subject-related fields. Research on spatial ability has made significant progress in the field of education. Educators and researchers are continually searching for methods to enhance students' spatial thinking and problem-solving ability, better preparing them for future challenges. Emerging technologies and tools like 3D modeling and 3D printing offer new opportunities in the study and education of spatial ability. The application of emerging technologies and tools like 3D modeling and 3D printing is of importance and significance in improving students' spatial ability. These technologies offer a range of unique educational opportunities and advantages that help nurture students' spatial thinking, design ability, creativity, and problem-solving skills. They provide students with practical application opportunities and lay a solid foundation for their academic and career development. However, there are still some shortcomings and challenges in research regarding the application of 3D modeling and 3D printing to enhance students' spatial ability.

(1) Complexity of Definition and Measurement. Spatial ability are multidimensional, including aspects such as spatial perception, spatial memory, spatial navigation, and spatial thinking. These dimensions are interrelated but can also exist independently. Furthermore, spatial ability span across multiple disciplinary areas, including psychology, education, geography, engineering, and more. The multidimensional and interdisciplinary nature of spatial ability research requires researchers to select specific dimensions and perspectives for their studies, potentially leading to the neglect of other important dimensions. Additionally, the interactions

between different dimensions further complicate the definition and measurement. Thus, accurately defining and measuring this ability is a challenge because there are no universally accepted standards and measurement tools. Researchers and educators may choose different definitions and measurement tools based on their research goals and backgrounds, and selecting the appropriate tools and measurement methods for assessing spatial ability is critical. This may include the use of psychological tests, virtual reality simulations, surveys, and various other methods, but the selection of suitable tools and methods requires careful consideration.

(2) Diversity and Cultural Differences. Students' spatial ability may be influenced by their cultural, social, and educational backgrounds, and individuals from different cultural backgrounds may exhibit different spatial ability. Therefore, research needs to consider differences among students from various cultures, adding complexity to the research. This study's participants are Chinese university students, and research on their spatial ability needs to consider appropriateness and adaptability to this specific cultural background and age group. The diversity among university students is also a challenge. Students' backgrounds, academic fields, and interests can affect their spatial ability, so ensuring a sufficiently diverse sample is essential to obtain comprehensive data.

(3) Application of Emerging Technologies. In the current digital era, spatial ability are crucial for solving many real-world problems, such as geographic information systems (GIS), virtual reality (VR), augmented reality (AR), and robotics. Conversely, these emerging technologies and tools have the potential to be applied to enhance research on spatial ability, which is in line with the demands of the times. However, the use of emerging technologies and tools requires consideration of their applicability. Effective methods or assessment tools for improving spatial ability need to be developed based on the characteristics of the technology and tools. While emerging technologies such as 3D modeling and 3D printing have the potential to

enhance spatial ability, their application also faces challenges related to technology, resources, costs, and sustainability. Furthermore, more empirical, controlled studies are needed to compare the effectiveness of emerging technologies and tools with traditional methods in enhancing spatial ability.

(4) Integration of Educational Content: How to integrate emerging technologies and tools into educational practices to enhance students' spatial abilities is a complex task that requires attention to multiple research directions, and more work is still needed. In the current university education system, the improvement of spatial abilities and the application of 3D modeling and 3D printing are based on subject-specific education. From the research literature on the improvement of spatial abilities, most studies are designed for specific knowledge domains or skill learning in particular disciplines, developing training programs to cultivate students' spatial abilities. These studies integrate the development of spatial abilities into specific subject curricula, achieving the fusion of ability development with the learning of subject domain knowledge and skills, which has significant implications for educational practice. However, there is relatively less research on the independent enhancement of students' spatial abilities separate from specific subject domain knowledge and skill learning. There is also relatively limited theoretical and empirical research focused on interdisciplinary knowledge and skill learning specifically aimed at improving spatial abilities (i.e., the processing and communication of spatial information). Furthermore, the application of 3D modeling and 3D printing in university education primarily focuses on specific courses for STEM majors, such as graphics courses in engineering. Moreover, it is more oriented toward basic applications of 3D modeling and 3D printing based on the needs of specific subjects, such as using 3D printing to create models as teaching aids in subjects like mathematics, chemistry, medicine, biology, etc., as a means to enhance both spatial and subject-specific abilities. Few universities may rely on maker spaces (such as

libraries) to conduct short-term training on the use and operation of emerging practical technologies and tools like 3D modeling and 3D printing.

21st-century skills, also known as "future skills" or "core skills," refer to a set of abilities and competencies that are crucial in today's globalized, digital, and rapidly changing social and work environments. These skills are not only important educational goals but also play a crucial role in career development. The 21st century is the age of digitization, where technology's role in society, economy, and education is increasingly significant. Therefore, having spatial abilities can help individuals better cope with and utilize emerging technologies, and the application of emerging technologies can also better assist students in improving their spatial abilities. In the context of the development of 21st-century skills and emerging technologies, offering courses in 3D modeling and 3D printing to enhance students' spatial abilities is both necessary and important. The establishment of such courses is based on the cultivation of spatial abilities and new skills, constituting competency-based education (CBE), which differs from subject-based education and possesses a degree of independence. Moreover, these courses are open to students from various majors, making them interdisciplinary in nature. Therefore, the integration of emerging technologies into the educational practices of spatial ability development requires the development of effective course designs and teaching strategies.

2.5 Summary and Framework Design

2.5.1 Chapter Summary

The main purpose of this study is to develop a 3D modeling and printing course to enhance the spatial abilities of university students. Previous scholars have conducted a substantial amount of related research, proposed hypotheses, theories, and models, and conducted surveys or experimental studies. In the first section of the second chapter (Part one of Chapter two), a systematic review of the research outcomes related to spatial abilities is provided. Based on the literature review, an analysis and synthesis of the historical development, definition and connotation, constituent elements and classification, measurement methods and tools, differences, and correlations of spatial abilities are conducted to gain a deeper understanding of the characteristics of the dependent variable (spatial abilities) in this study. In the second section, building upon the foundation of the previous section, the possibility of improving spatial abilities is demonstrated through relevant literature research, and various methods and approaches to enhancing spatial abilities are analyzed and listed. Finally, the current research status of enhancing spatial abilities in subject-specific education is emphasized. In the third section, relevant theories in the field of education that focus on enhancing spatial abilities through 3D modeling and 3D printing are cited and analyzed, including spatial cognition theory, multimodal theory and multimodal learning, and cognitive development theory (constructivism). Finally, some typical course development models are listed and analyzed, with a particular focus on blended course development models. The fourth section of the article discusses the integration of 3D modeling and 3D printing-based courses to enhance students' spatial abilities. Based on the explanation of the concepts, principles, and processes of 3D modeling and 3D printing, an analysis of the integration of 3D modeling and 3D printing with the aforementioned relevant theories is provided. Lastly, the current research status and the opportunities and challenges faced in the application of 3D modeling and 3D printing to enhance students' spatial abilities are analyzed.

2.5.2 Framework Design

Based on the literature review and theoretical analysis above, the conceptual framework of this research is proposed, as shown in Figure 7. With the aim of developing a 3D modeling and 3D printing course to enhance the spatial abilities of university students, this study primarily addresses the following questions: Why should we improve the spatial abilities of university students? How can we enhance the spatial abilities of university students? Why should a 3DMP course be offered? How should a 3DMP course be developed? How can we measure the spatial abilities of university students? Does the 3DMP course improve the spatial abilities of university students? What are the specific outcomes of the enhancement of spatial abilities? The research is primarily composed of three major modules, namely spatial abilities, theoretical framework, and 3D modeling and 3D printing. These three modules interact with and influence each other. Spatial abilities serve as the starting point of the research and are also the dependent variable. The construction and measurement of spatial abilities are based on relevant theoretical foundations. The 3D modeling and 3D printing course is the outcome of the study and serves as the independent variable. The characteristics of the 3D modeling and 3D printing course also affect the application of spatial abilities and relevant theories. Based on these three major modules, the entire research framework is designed as follows:

Firstly, through a review of the literature and an analysis of the characteristics of spatial abilities, the research addresses the questions of why university spatial abilities need to be improved and how to enhance the spatial abilities of university students. The analysis of relevant measurement theories and methods also paves the way for measuring the effectiveness of spatial ability enhancement.

Secondly, by analyzing relevant theories, the research establishes a theoretical foundation for the study of enhancing spatial abilities through 3D modeling and 3D printing courses, guiding the development and implementation of these courses.

Thirdly, the research analyzes the characteristics, processes, and methods of 3D modeling and 3D printing technology and tools. Building on the analysis from the previous two steps, it addresses the questions of why 3D modeling and 3D printing courses should be offered and how to design and implement these courses.

Fourthly, through the implementation of the courses and the measurement of spatial abilities, the research addresses its main question: whether 3D modeling and

3D printing courses improve the spatial abilities of university students. Combining the relevant theories, principles, and evaluation methods discussed above, the research analyzes and discusses the specific outcomes of spatial ability enhancement, forms feedback results, and provides constructive suggestions to guide the improvement and dissemination of the courses.

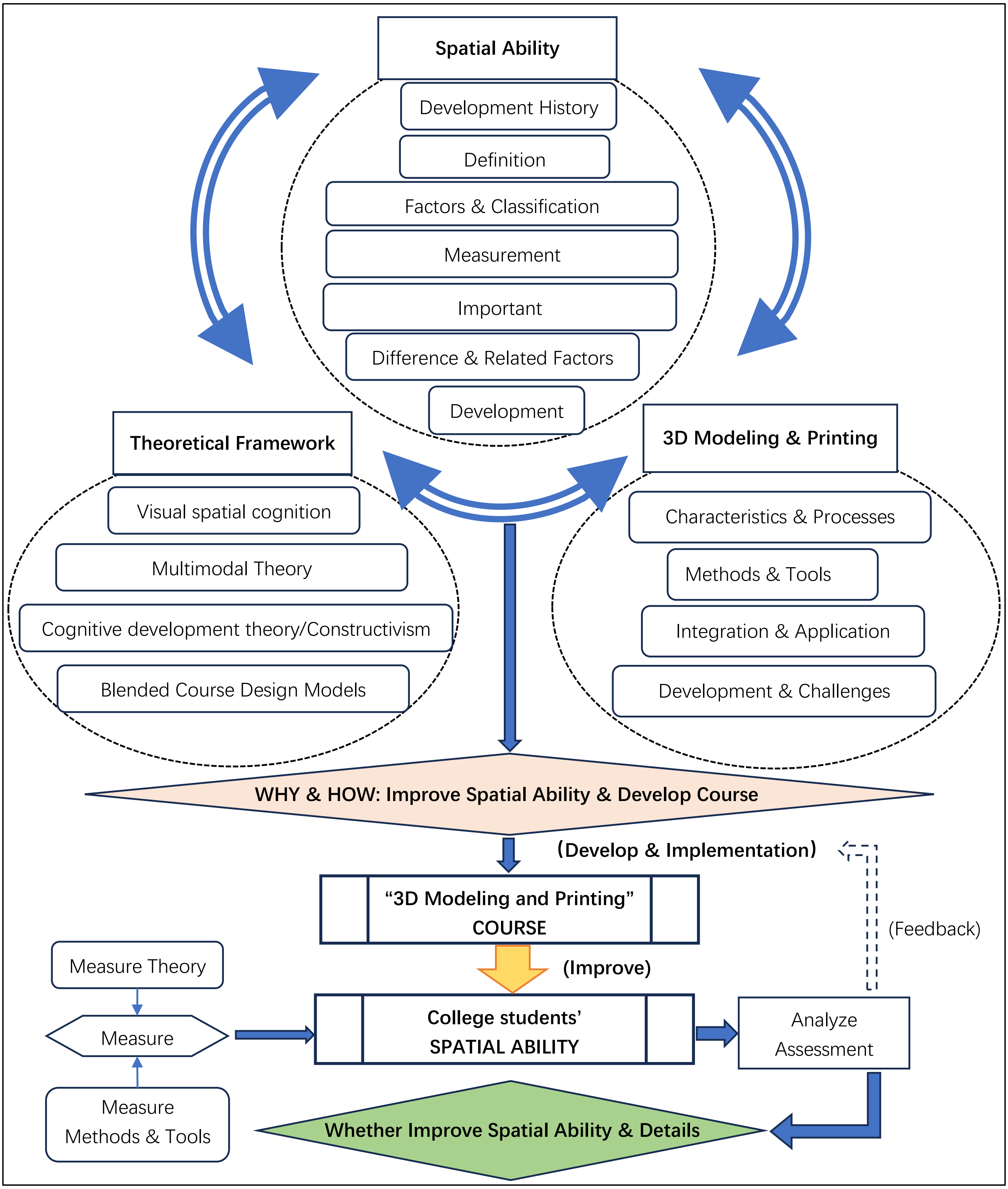


Figure 7 Conceptual Framework

CHAPTER III

RESEARCH PROCESS & METHODS

3.1 Research Framework and Process

Based on the main research purpose of improving college students' spatial abilities through the introduction of 3D modeling and printing, as well as relevant theories, the entire research is mainly divided into four stages: Contextual and Theoretical Research, Curriculum Design and Construction, Curriculum Implementation and Monitoring, and Analysis and Evaluation. The entire research framework and process are illustrated in Figure 8. Different research methods are used in each research stage to achieve distinct research objectives.

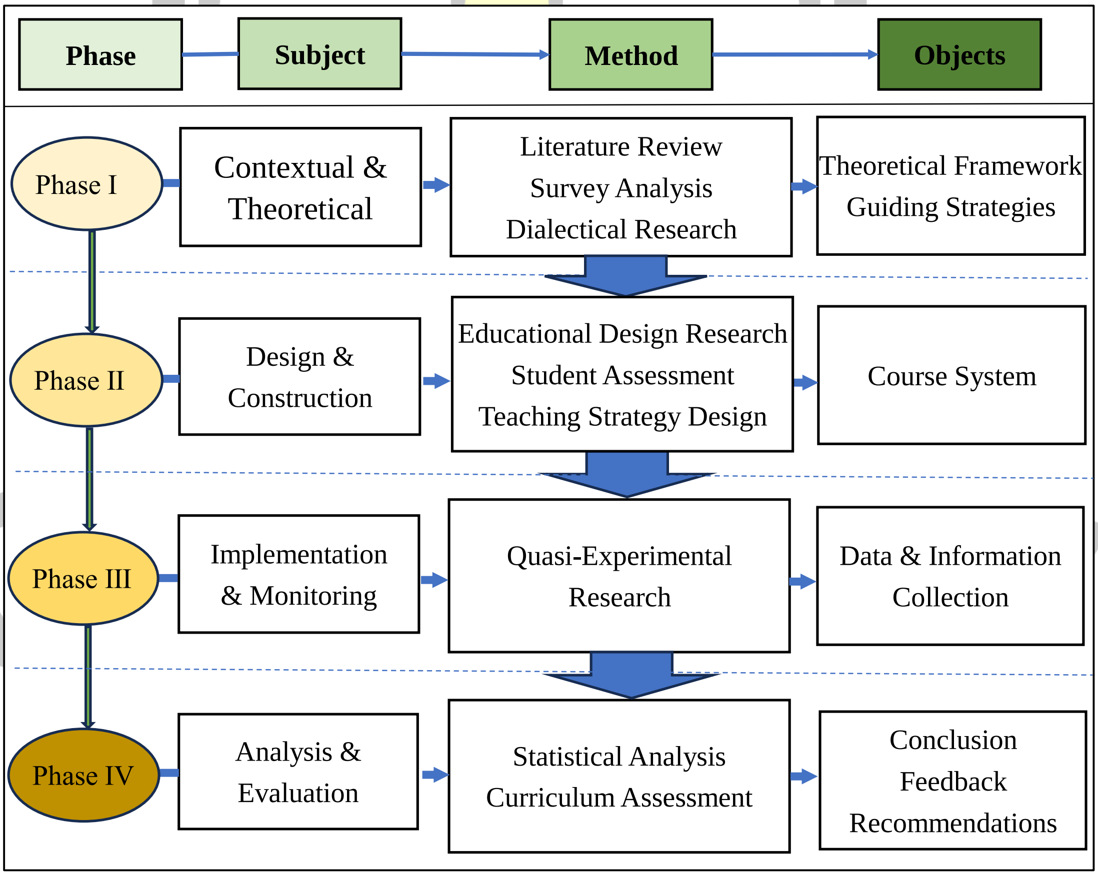


Figure 8 Research Framework and Process

In the first stage, survey analysis, literature review, and dialectical research were employed. The survey analysis primarily investigated and analyzed the research findings related to spatial ability, the characteristics and applications of 3D modeling and 3D printing, as well as the relevant theories and research status supporting the enhancement of college students' spatial ability through 3D modeling and printing. Literature review and dialectical research were conducted to establish the theoretical framework that underpins this study and provide the necessary guidance, strategies, and methods for the subsequent research stages.

In the second stage of the research, with the support of the first stage, methods such as educational design research, student assessment, and teaching strategy design were employed to design and construct an applicable and effective curriculum system for 3D modeling and printing.

The third stage is the implementation and monitoring phase of the curriculum. In this stage, a quasi-experimental research approach is employed to implement the curriculum system designed in the second stage. Students' spatial ability is measured, and the progress of the curriculum implementation is monitored.

The final stage of the research involves statistical analysis of the data and information collected during the implementation phase, as well as curriculum assessment. This stage aims to generate research conclusions and teaching feedback based on the analyzed data and information. Additionally, constructive opinions and recommendations are provided.

3.2 Phase I Contextual & Theoretical Research

In this stage, the background related to the research topic was first investigated and analyzed. This included policies, reports from various countries, market conditions, and the current state of research. Following that, a survey analysis was conducted to gather evidence and analyze the research findings related to spatial abilities, the characteristics and applications of 3D modeling and 3D printing, as well as the relevant theories and research supporting the enhancement of college students' spatial abilities through 3D modeling and printing. Through literature review and dialectical research, a theoretical framework supporting the conduct of this research was developed. It laid the foundation for the implementation of subsequent research stages and provided corresponding guiding strategies and methods.

In this stage, we aim to address five of the research questions mentioned in Chapter One, namely: ① Why should we enhance the spatial ability of university students? ②How can we improve the spatial ability of university students? ③Why should we develop 3D Modeling and Printing course for university students? ④How can we implement 3D Modeling and Printing course for university students?⑤How can we measure university students' spatial ability and their changes? By addressing these questions, we intend to demonstrate the importance, necessity, applicability, and effectiveness of offering a 3D modeling and printing course to enhance college students' spatial abilities. The relevant research processes and results are elaborated upon in the preceding two chapters.

Here, as an example, we provide a detailed description of the research process and methods in the context of "The Current State of Research on the Application of 3D Modeling and 3D Printing to Enhance Students' Spatial Ability".

This analysis set the timeframe for looking for relevant papers to be between January 1, 2010, and December 31, 2022. In the study, electronic databases were searched using specific keywords, and the related references were manually searched. The research articles were identified to scan for additional articles and eventually create a comprehensive data pool. Three separate databases were searched: ERIC, Scopus, and ProQuest (limited to academic journals).

In the current analysis, the two following sets of keywords were used: (a) keywords related to spatial ability, including "spatial skill*", "spatial *abilit*", "spatial thinking", "spatial cognition", "mental rotation", “visuospatial”, "spatial visualization". (b) keywords related to 3D modeling, including “3D modeling”, “three-dimensional modeling”, “3D CAD”, “3D computer-aided design”. (c) keywords related to 3D printing, including “3D printing”, “Additive Manufacturing”, “rapid proto-typing technology”. Additionally, we searched and chose synonyms for virtual technologies and spatial ability in the relevant literature to supplement search terms.

A Boolean OR operator joined the keywords in each collection first, and then the Boolean AND operator was used to combine the keywords in both collections to achieve the complete and appropriate combination. In each database, citations were extracted from each search and imported into Endnote to extract duplicates.

3.3 Phase II Curriculum Design and Construction

3.3.1 Preliminary Analysis

3.3.1.1 Needs Analysis of Students, School and Society

Student Needs Analysis

The offering of 3D Modeling and Printing course in universities can meet various demands for students, including enhancing their spatial abilities, innovation skills, and competitiveness in the job market.

(1) Technical Needs: a. 3D printing technology is rapidly advancing and widely applied across various industries, including manufacturing, healthcare, arts, and design. Therefore, cultivating students' ability to master this technology is crucial for their future career development. b. Students need to understand 3D modeling software and tools to be able to design and create their own 3D models, which is essential for solving real-world problems and fostering innovation.

(2) Innovation and Design Needs: a. 3D modeling and printing technologies provide an innovative platform for addressing real-world issues. Students can develop their innovative abilities by designing and printing prototypes to bring their creative ideas to life. b. Acquiring these skills helps students better comprehend design principles, spatial layouts, and structures, enhancing their capabilities in engineering, design, and architecture.

(3) Interdisciplinary Needs: a. 3D modeling and 3D printing are not limited to engineering and design; they are applicable to other disciplines such as life sciences, history, arts, and geography. Therefore, these courses can help students establish interdisciplinary connections and applications across multiple fields. b. Students can combine their spatial abilities learned from these courses with knowledge from other disciplines to better address complex problems and projects.

(4) Employment Market Needs: a. Graduates with expertise in 3D modeling and 3D printing are highly competitive in the job market. Many companies and industries require professionals to handle tasks related to 3D modeling and printing, including manufacturing, medical devices, construction, and media production. b. Students can lay a solid foundation for their career development by acquiring these skills, increasing their opportunities for finding jobs and career advancement.

School Needs Analysis

In 2021, the school proposed to deepen education and teaching reform, implement the fundamental task of fostering virtue and talent, further strengthen the curriculum's focus on character education, improve the general education system, enhance the level of general education, and improve the quality of talent cultivation to meet the needs of talent cultivation in the context of "New Normal Education" for teacher training, humanities, engineering, agriculture, and medicine. The school decided to initiate a project proposal for the construction of a batch of general elective courses. Among them, in the category of "Natural Science and Technology," it was pointed out that this type of course mainly covers mathematics, physics, computer science and technology, engineering technology, and logical thinking, aiming to cultivate students' mathematical thinking and logical reasoning abilities, understand and organize the importance of knowledge and engineering technology to human society, and help students improve their mathematical and scientific literacy and engineering awareness.

Social Needs Analysis

Spatial ability is an important aspect of intellectual development, and the quality of modern technology talents is closely related to the possession of strong spatial abilities. The development of spatial imagination also influences a person's overall capabilities. The 21st century is an era of modern talent, and comprehensive development of individuals is essential to meet society's demands for talent. The demonstration of comprehensive abilities is particularly important. With the rapid development of the information society and the rise of curriculum reform, the formulation of the objectives of this course should align with the trends of social development, cater to societal needs, and be timely and forward-looking. Therefore, the establishment of this course should also meet the requirements of the innovative era, nurturing individuals with abilities such as innovative thinking, spatial thinking, and interdisciplinary thinking for society.

3.3.1.2 Requirement Analysis

According to the "Jiaying University General Elective Course Construction Standards", general elective courses need to meet the following requirements:

In line with the general education concept, guiding students to explore a wide range of knowledge areas in different disciplines, enhancing their understanding of themselves, society, nature, and their interrelationships, cultivating sound character, tolerance, a broad perspective, critical thinking, a strong sense of social responsibility, and humanistic care, as well as a pursuit of truth.

Course content needs to adhere to the following four principles:

Fundamental: Beneficial for students to understand the most fundamental knowledge domains and thinking methods of humanity.

Integrative: It should integrate and provide a comprehensive understanding of content from various disciplinary fields.

Guiding: It should contribute to the development of students' comprehensive rationality, healthy personality, and positive emotions.

Universal: It should not require prior systematic knowledge in a specific major, making it suitable for students from various academic backgrounds.

For each course offered, if the enrollment reaches 30 students or more per semester, one teaching section can be opened. The course hours and credits are 32 hours per semester/2 credits.

3.1.1.3 Teaching and learning Environment Analysis

The environment is relative to specific activities and constitutes the conditions necessary for their continuous operation during the process. The teaching and learning environment refer to all the conditions required for the smooth conduct and maintenance of teaching and learning activities, including both material and non-material conditions.

In terms of material conditions, with the continuous development of information technology and educational technology, universities in China are now equipped with corresponding multimedia facilities. Some have even established smart classrooms. Hardware infrastructure is relatively well-established, and there is a rich array of cognitive tools and teaching and learning spaces.

Universities have multiple computer labs that can cater to various computer-related courses. Additionally, the majority of university students own personal computers, which make it more convenient for them to complete learning tasks outside of class.

This school provides Maker Space for student organizations, equipped with 10 3D printers, which facilitate students in operating, using, and completing 3D printing tasks for their projects.

There are many open-source and free 3D modeling and slicing software options available, ensuring the smooth execution of teaching and learning activities.

The developed network and abundant online resources provide the conditions necessary to enrich teaching and learning activities.

Today's university students each have a smartphone, which enables the possibility of conducting online spatial ability tests.

In terms of non-material conditions, university students are intellectually active, enjoy communication and collaboration, exhibit clear learning motivation, are observant and thoughtful, and can complete learning activities with teacher guidance.

Furthermore, the widespread outbreak of the COVID-19, along with the highlighted advantages of online courses and flipped classrooms, has guided us towards the need for educational model reforms.

3.3.2 Curriculum Model Construction

3.3.2.1 ADDIE Instructional Design Model

Curriculum development requires comprehensive consideration of various aspects to ensure that the design and implementation of the curriculum can achieve the intended educational objectives and meet the needs of students, schools, and society. The curriculum development model is a systematic approach used to plan, design, and implement educational programs. For the specific design of this course's teaching, guided by the relevant theories mentioned earlier, the primary focus is on using 3D modeling and 3D printing to develop students' spatial abilities. Additionally, modifications and refinements have been made to the classic ADDIE instructional design model, serving as the general teaching process for this research, as shown in Figure 9.

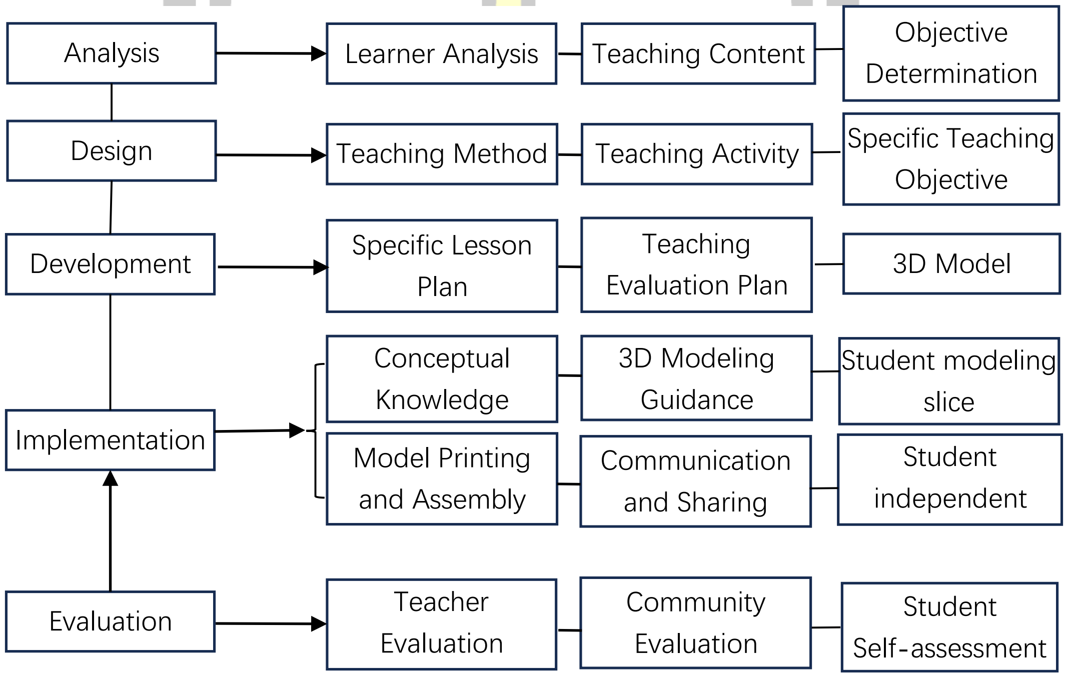


Figure 9 Instructional Design Model based on ADDIE

The ADDIE instructional design model is a scientifically structured approach for effective teaching and primarily involves determining what students need to learn, which is the establishment of learning objectives; how students need to learn to achieve the learning objectives, which involves the application of learning strategies; and how to assess the effectiveness of learners, which involves the implementation of learning assessment. The main elements of the ADDIE instructional model include Analysis, Design, Development, Implementation, and Evaluation.

(1) Analysis Phase

The analysis stage, as the foremost step in teaching practice, ensures the smooth progress of the teaching process. The author first analyzes factors such as learner analysis, learning objectives analysis, and content analysis to understand the real-life situation of students, ensuring that the teaching process proceeds smoothly and effectively. Every effort is made to improve the teaching effectiveness of each class.

(2) Design Phase

Following the analysis of the relevant factors mentioned above, the author will design specific teaching objectives for each class and design 3D printing teaching activities oriented towards developing students' spatial abilities. To address different levels of spatial ability development, the author follows the principle of a spiral ascent in arranging and designing the content and activities. The design of content and activities should align with students' cognitive abilities and real-life situations, and each teaching module should be as compatible as possible with the development of spatial abilities.

(3) Development Phase

The curriculum development phase mainly involves preparatory work before the implementation of the curriculum. This includes understanding the course objectives based on the preliminary needs analysis, determining the entire course's objectives, preparing relevant course materials required for class, and preparing evaluation methods and cases. The evaluation methods will be detailed in the evaluation phase.

(4) Implementation Phase

This phase follows the analysis, design, and development stages and enters the implementation stage. During this stage, teachers will explain relevant knowledge concepts, guide students in modeling and slicing, and organize students in physical assembly and exploration. Through this process, the effectiveness of this instructional design will be validated. Simultaneously, based on students' classroom feedback and teachers' post-class reflections, the curriculum will be continuously optimized to ultimately achieve the teaching objectives.

(5) Evaluation Phase

The evaluation stage occurs after the implementation stage. When teachers are in the teaching process or after completing their teaching work, they need to evaluate students' learning outcomes. This includes assessing students' performance in the classroom and evaluating their creative works after the course. This includes formative assessment and summative assessment. In this evaluation process, it is not just the teacher's evaluation of students but also includes students' self-assessment and peer assessment. Through this evaluation process, shortcomings in students' classroom learning outcomes and creative works can be identified for improvement, and the curriculum design can be continuously refined.

3.3.2.2 Teaching Requirements for Improving Spatial Ability

The ultimate goal of teaching is to cultivate students' spatial abilities, which are achieved under the guidance of theories such as spatial cognition, multimodal theory, cognitive development (constructivism), and others analyzed earlier. Combined with the previous analysis, an analysis of the teaching requirements for the 3D modeling and printing course can be conducted.

(1) One of the principles of constructivism emphasizes students learning by doing and encourages students to acquire and apply knowledge through activities and practical operations. It allocates more time for students to engage in hands-on activities in the classroom, allowing them to experience the joy of creativity, develop their innovative abilities through practical experiences, and complete teaching tasks through collaboration and communication. The teaching process should emphasize learning by doing, harnessing students' initiative in learning.

(2) Project-based learning is a way for students to creatively solve problems, focusing on projects as the central theme. It hopes that students can learn knowledge through collaborative group work. In the teaching process, this concept should be incorporated, allowing students to engage in cooperative learning based on projects and complete teaching tasks.

(3) Fully utilize network technology. At the present stage, there have been many technological breakthroughs in teaching, and there are many devices and networks that serve teaching. The emergence of these technologies has made online teaching possible and better adapted to students' learning progress, motivating their desire to learn.

(4) In constructivist teaching, the role of the teacher needs to change from being an instructor to becoming a guide and supporter of student learning. The teacher's role is to provide students with project-based scenarios and to offer analysis and problem-solving methods when students encounter difficulties in the learning process. This helps students internalize knowledge.

（5）Fully Utilize Multimodal Theory. A teaching environment with multiple representation modes can achieve complexity, animation, and interactivity. It can simulate real-world objects and states in digital virtual space, providing a rich variety of information through multiple representation modes. Teachers and students can easily access and retrieve this information using user terminal devices. Exploring the enhancement of spatial abilities based on multiple representation modes includes organizing teaching activities, designing learning environments, devising teaching strategies, and selecting assessment criteria. The 3D modeling and printing curriculum system itself possesses a multimodal learning system, offering various forms of information through multiple representation modes. This system helps students observe demonstrations of 3D modeling, access learning materials such as physical images, engineering drawings, and micro-videos demonstrating 3D CAD modeling skills. Students can also submit and share their design work, ultimately leading to the 3D printing of their creations.

3.3.2.3 Principles of Curriculum Development

(1) Student-Centered Principle

In the context of this study, which involves 3D modeling and 3D printing courses, it differs from traditional courses in that it requires strong hands-on skills from students. Therefore, when constructing the teaching model for 3D modeling and printing, it is essential to prioritize students' cognitive characteristics and learning styles. The design of teaching activities within the teaching model should be student-centered, taking into account the course content and students' cognitive patterns. This approach allows students to have an active role in the learning process and enables them to understand knowledge through practical application. Prioritizing students means believing in their ability to solve learning problems independently, respecting their unique ideas, and relying on them to complete assigned projects. It encourages active thinking, bold experimentation, and fosters innovation. Furthermore, teachers should adapt teaching content to students' individual differences and integrate various online and real-world resources to facilitate learning based on students' existing knowledge while also encouraging them to explore new knowledge actively.

(2) Openness Principle

The openness principles entail providing diverse learning resources and evaluation methods. Openness in learning resources is facilitated through multimedia and the internet, creating a varied online learning environment that offers students a wide range of learning resources and communication methods. This approach removes the constraints on students' learning attitudes and content imposed by textbooks and teachers' perspectives. For instance, in the construction of the 3D digital modeling teaching model, the delivery of course content occurs online, allowing students to choose from different content for their learning. This approach provides students with diverse learning resources that go beyond mere search engine results or a collection of resource links. It consists of a high-quality, well-structured knowledge repository that helps students acquire a systematic understanding of the subject matter. Additionally, the openness of learning resources should extend to interdisciplinary connections. No knowledge is isolated, and there are inseparable links between seemingly independent disciplines. Therefore, when designing teaching objectives based on the openness principle, attention should be paid to the connections between subjects. For example, while constructing the 3D digital modeling teaching model to prepare students for developing spatial abilities, the relevance of mathematical and geometric knowledge to students' spatial abilities should be considered.

Openness in evaluation methods implies that the assessment of teaching results should not be limited to teachers' reference materials, expert-set standards, or standard answers. Instead, it promotes diverse assessment methods. In the development of the 3D modeling and 3D printing course, the assessment approach emphasizes diversity by incorporating not only traditional teacher evaluations but also peer evaluations by students. Additionally, students' works will participate in a maker education competition, where an evaluation panel will assess their creations. This multi-dimensional approach ensures that the evaluation process is open and that the forms of assessment are diverse.

(3) Standardization Principle

Standardization refers to innovating traditional teaching models while preserving their advantages. It involves using advanced auxiliary technologies for online self-study, transforming the traditional teacher-student relationship, and extending the classroom in a spatial sense. This approach acknowledges the superiority of traditional teaching models while also promoting innovations in teaching methods.

Furthermore, when setting teaching objectives for 3D modeling and 3D printing courses, emphasis should be placed on students' experience and insights into information technology and information culture. It aims to cultivate students' innovation and spatial imagination. The teaching model for 3D modeling and printing courses consistently pursues the same teaching objectives in every class, unified under the overarching goal of achieving students' spatial abilities. Thus, the teaching model is standardized to reach its ultimate teaching objectives.

（4）Diversity Principle

Diversity means that the teaching model is not fixed but can be adjusted according to the content of each class. The students being taught change throughout the entire teaching process, and the content being taught is continually updated. From a student's perspective, their learning levels also vary. These uncertainties mean that the construction of the teaching model cannot be uniform. Trying to use a fixed method to address changing teaching situations will hinder the achievement of good teaching results. In this study, the teaching model for 3D modeling and printing courses adheres to the principle of diversity. In the classroom, students collaborate on designing models based on projects, fostering their subjectivity and providing them with more autonomy and flexibility in their learning space.

3.3.3 Practical Design

3.3.3.1 Learner Analysis

Systematic research and assessment of the learning situation and characteristics of college students are helpful for educators to better understand the needs of students and meet their educational requirements. In addition to the general characteristics of college students, a specific focus here is on the differences in students' majors, including STEM (Science, Technology, Engineering, and Mathematics) majors and non-STEM majors. This requires considering the universality and difficulty of course content. For example, the choice of 3D modeling software needs to be carefully considered, as overly specialized 3D CAD software can not only lead to tight schedules but also decrease the interest of students, especially those in non-STEM majors. Furthermore, differences in students' levels should also be taken into account. Although college students generally have some computer software proficiency, the students enrolled in the course come from a pool of thousands of students, including different grades (primarily sophomores and juniors), which naturally results in differences in their cognitive levels. This necessitates differentiated instruction. For instance, students with a foundation in CAD should be allowed to choose their 3D CAD software for 3D modeling, focusing more on innovative design of models. In the course content design, the principle should be to progress from fundamental learning to advanced exercises while providing abundant teaching resources to assist students facing learning difficulties. Additionally, in the context of 3D printing, leveraging maker spaces allows students to learn from and guide each other.

3.3.3.2 Educational Objectives

Considering the challenges posed by the technology-based enhancement of spatial abilities, the course design incorporates new objectives in addition to learning 3D modeling and 3D printing knowledge and skills. These new objectives aim to enhance students' drafting abilities, promote the construction of clearer spatial concepts, and cultivate their spatial abilities. The spatial ability enhancement program emphasizes visual-spatial cognitive activities, enabling students to use 3D CAD for designing and drawing three-dimensional models, followed by 3D printing to create the models. This facilitates the visualization, presentation, and communication of the main components of the teaching activities. The overall objectives of the course are elaborated upon in terms of knowledge and skills, processes and methods, and emotional attitudes and values, as shown in Table 5.

Table 5 Three-Dimensional Objectives of 3DMP course

Dimensions	Detailed objectives
Knowledge and Skills	★Identify and understand basic geometric shapes, including rectangular prisms, cylinders, spheres, and cones. ★Learn to create orthographic projections (front, side, top views) of design projects, read and interpret orthographic projections, and construct them in 3D CAD. ★Master the methods of describing positions using coordinate systems and describing the movement and transformation of shapes using coordinate systems. ★Understand basic operations involving spatial relationships. ★Acquire proficiency in the basic operations of 3D modeling software and slicing software, including importing/exporting, view switching, extrusion, rotation, sketching, Boolean operations, and more.
Processes and Methods	★Foster students' ability to recognize and understand graphical representations. ★Cultivate students' drawing and interpretation skills through the creation of orthographic projections and model construction. ★Develop students' ability to explore shapes through hands-on experimentation, testing, and calculations. ★Cultivate students' hands-on skills in designing and 3D printing.
Emotional Attitudes and Values	★Through practical activities in the course, such as design, printing, and evaluation of works, enable students to perceive the charm of the integration of 3D modeling and 3D printing. ★Instill good habits of creating precise drawings and fostering critical thinking skills.

3.3.3.3 Course Outline and Schedule

The course "3D Modeling and Printing" is a public elective course in the university. The public elective courses of the whole school are offered by teachers themselves and uploaded to the teaching system of the school after being approved by the school. Students can choose corresponding courses on the network to complete the credit requirements of their studies. If the number of students for elective courses is reached (generally at least 30), the public elective courses of the whole school can start. Information about this course is shown in Table 6 below.

Table 6 Outline of "3D Modeling and Printing"

Course	3D Modeling and Printing				
Credit	2	**Modular**	Natural Science and Technology		
Weekly class hour		1.5 hours	**Total class hours**	24 hours	
Students	Students who choose this course, regardless of major and grade				
Course introduction					

With the continuous development of computer aided design technology, 3D solid design has been widely used in various fields because of its strong interactivity, good operability, high precision, easy modification, easy communication and other advantages. In order to improve college students' understanding of 3D entity design, promote the progress of computer aided design technology in the field of college education, and cultivate students' design thinking, hands-on ability and innovation spirit, this course is hereby offered. The center and focus of the course content: the operation and application of 3D One software and the operation and use of 3D printers General characteristics of the course: combination of theory, experiment and practice Assessment and score recording method: the students' 3D design models and 3D printing works are scored as the main assessment scores of the courses.
Instructional objectives
1. Understand the development and basic principles of 3D printing; 2. Understand and master the operation and use of 3D One software; 3. Learn the operation and use of 3D printer; 4. Design and make 3D models.

The course "3D Modeling and Printing" mainly consists of three parts: learning and using 3D One software; Operation and use of the printer; Design and production of 3D objects. In terms of course structure, it begins by providing students with various resources related to 3D modeling and 3D printing (including videos) to generate interest in the course. This initial phase also covers the history, applications, and future developments of 3D modeling and 3D printing. Following that, students engage in a series of model constructions using 3D modeling software. The selection of models starts from simple ones and progressively advances to more complex ones. The modeling methods and required commands also build upon each other. Once the models are completed, students proceed to operate a 3D printer to bring their models to life through 3D printing. The course schedule is as shown in Table 7.

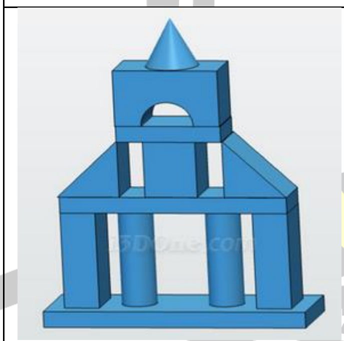
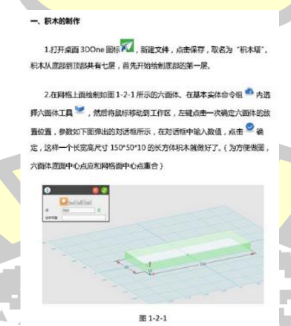
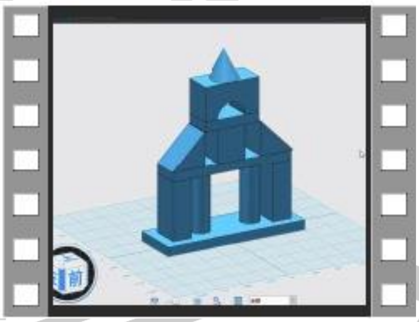
Table 7 Schedule of "3D Modeling and Printing"

Week No.	Course Content	Classroom Location
2	Course Introduction, Spatial Ability Test(pre-test)	Multimedia Classroom
3	Introduction to 3D Modeling and 3D Printing	
4	3D One Installation and Overview	Computer Laboratory
5	Building with Blocks	
6	Hanoi Tower Design	
7	Desk and Chair Design	
8	Table Lamp Design	
9	Pen Holder/Vase Design	
10	Teacup Design	
11	3D Slicing and 3D Printing Machine	
12	Printing Practice (Computer and Mobile Design)	Group1: Maker Space
13	Printing Practice (Picture Frame Design)	Group2: Maker Space

14	Printing Practice (Bicycle Design)	Group3: Maker Space
15	Printing Practice (Carousel Design)	Group4: Maker Space
16	Printing Practice (My Home)	Group5: Maker Space
17	Conclusion, Spatial Ability Test(post-test)	Multimedia Classroom
Note: Printing Practice are grouped, with the current group completing the 3D printing in the Maker Space, while other groups study online. In case of COVID-19 restrictions preventing offline learning, all courses except for the printing course can be converted to online courses (with online course content already developed).		

The teaching content is mainly through the explanation of cases, so that students can learn and operate with reference to cases. Taking the module "Learning and using 3D One software" as an example, one section is about "building blocks", some of which are shown in the table below.

Table 8 Teaching content—building blocks

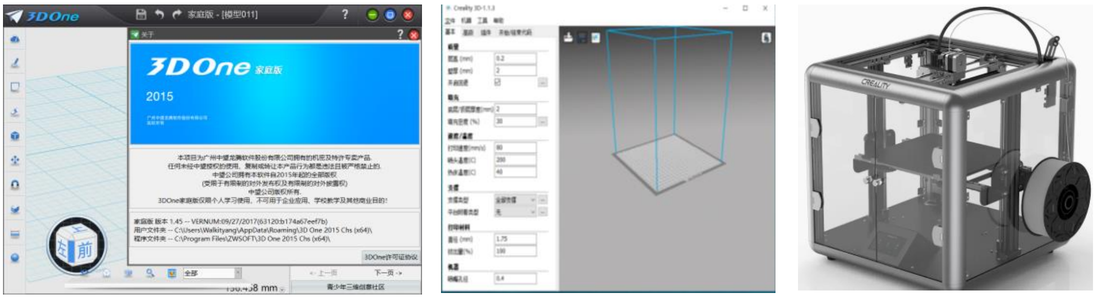
Introduction		
Building blocks are one of our favorite toys when we were young. We can use building blocks to build bridges, houses, castles and other building models. Let's use 3D One software to design our own building blocks.		
Learning objectives		
1. Be able to use 3D One software to make basic solid structures with a certain size; 2. Learn to use array commands to copy entities; 3. Learn how to adjust views; 4. Be able to adjust the spatial position of different entities; 5. Learn to add and subtract with Boolean operation.		
Cases and Resources		
 Case	 Document	 Video
Outward bound training		
We can also use building blocks to build bridges, houses, overpasses and other buildings. You can use the methods and technologies you just learned to build the following entities, or build your own unique buildings.		

3.3.3.4 Textbooks and Resources

The reference textbooks used are shown in Figure 10 below.

Figure 10 Reference Textbooks of Course

The teaching aids include: Multimedia; Computer; 3D One and Cura software; 3D printer. Multimedia is used to explain knowledge content; Computers equipped with 3D One and Cura software are used for students' 3D modeling and model slicing before printing; The 3D printer is used for 3D printing of models, and the attached tools are used for the processing of printing. Relevant software and 3D printer are shown in Figure 11.



① 3D One software ② Cura software ③ 3D Printer

Figure 11 Relevant Software and Instrument

3D One is a 3D design software developed based on STEAM concept and provided for national youth education. 3done is committed to improving students' thinking ability and realizing the development of innovative quality education. Therefore, 3DOne has a simple and easy-to-use program environment, which supports professional graffiti style plane sketch drawing. It can carry out rich and practical 3D entity design, provide a variety of display controls, and download 3D printing models through community websites embedded in the software. 3D One combines these powerful functions with a simple and easy-to-use program environment to make it easier for students to get started.

Cura is an open-source 3D printing slicing software designed by Ultimaker Company, with the design goal of "high integration" and "easy use". It contains all the functions required for 3D printing, including model slicing and printer control. Cura is easy to use because of its simple menus and commands; The powerful function and efficient slicing speed are popular among users. It is one of the most commonly used entry-level slicing tools.

The 3D printer “Sermoon-D1” was developed and produced by the CREALITY 3D company. Its related parameters are shown in the following table.

Table 9 The 3D printer “Sermoon-D1”

Molding technology	FDM	**Material**	PLA/ABS/TPU
Print Size	280*260*310mm	**Accuracy**	±0.1mm
Layer Thickness	0.1-0.4mm	**Injector**	No.: 1; Φ: 0.2/0.4/0.6mm

The course uses four online platforms: WeChat groups, CHAOXING Online Course Platform, 3Done Community, and WENJUANXING (SURVEYSTAR).

The use of WeChat groups is for its efficiency in: Teaching notifications and reminders (sending important teaching notices, course schedules, and reminders to ensure students are informed about course information in a timely manner); Course discussions and Q&A (for discussions and addressing questions among students, allowing students to raise questions anytime, anywhere, with both teachers and classmates providing assistance and answers); Resource sharing (sharing teaching resources such as slides, documents, links, etc., to facilitate students' access to study materials).

This course primarily uses the CHAOXING Online Course Platform to upload course materials, enabling students to engage in independent online learning, as shown in Figure 12.

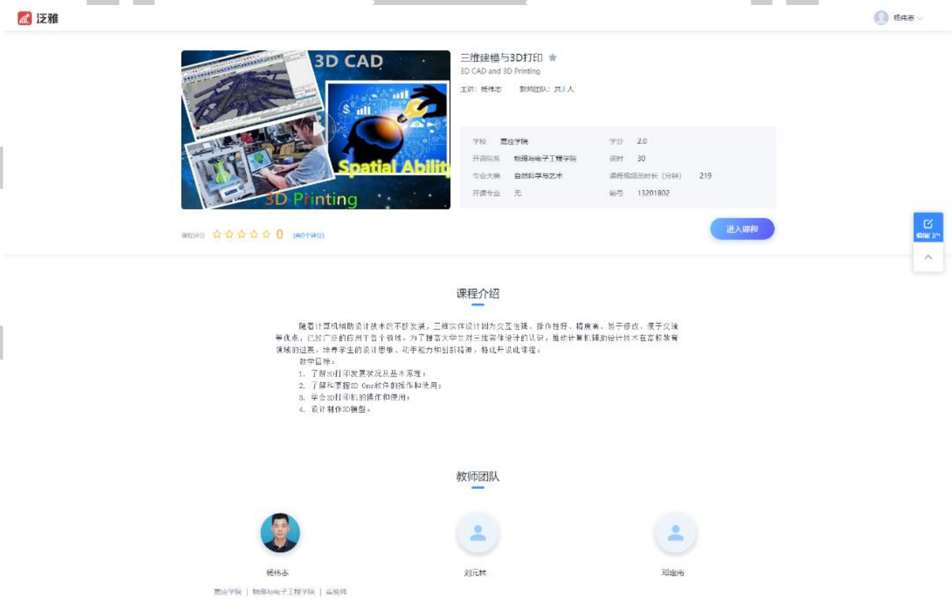


Figure 12 CHAOXING Online Course

The 3DOne community offers a wealth of related online resources. Students can download software, access information, view case studies and works, and participate in related competitions within this community. Most importantly, students can upload the 3D models they create to this community, and once approved, they will be displayed on the community webpage, as shown in Figure 13, which features some of the uploaded works.

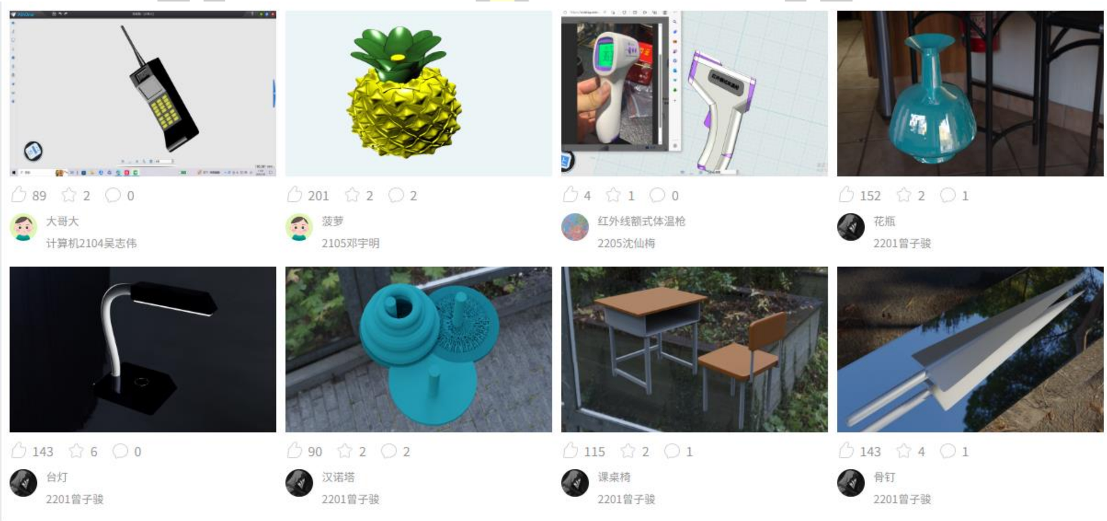


Figure 13 Some Models on 3DOne Community

WENJUANXING (SURVEYSTAR) is mainly used for spatial ability test.

3.3.3.5 Teaching Methods and Strategies

The course is carried out by combining theoretical explanation with practical operation. This course primarily employs three teaching methods, namely, lecture method, flipped classroom, and practical guidance, as shown in Figure 14. The lecture method involves teachers imparting knowledge to students through verbal explanations, demonstrations, and presentations. It is used for introducing the concepts of 3D modeling and 3D printing, as well as covering topics related to slicing software and 3D printers. For the section on 3D modeling, various learning requirements, operational procedures, case studies, and related materials have been uploaded to the website. Students can independently study these course materials before class, and classroom time is dedicated to discussions and problem-solving. Therefore, the flipped classroom approach is utilized for the 3D modeling content. Recognizing the practical nature of 3D modeling and the hands-on aspects of the 3D printing process, practical guidance is employed for the module on the 3D printing process.

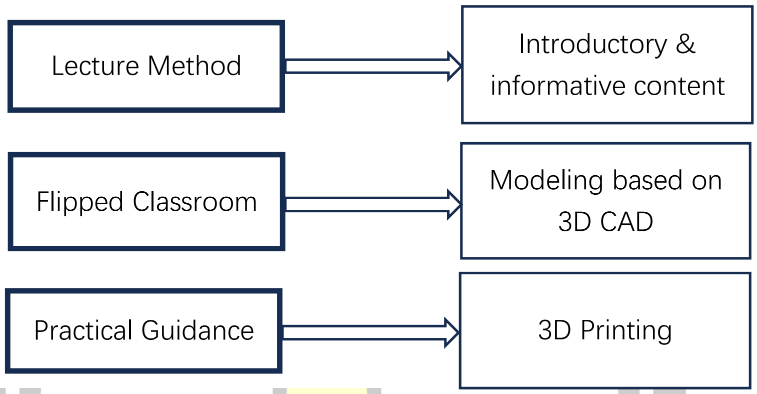


Figure 14 Teaching Methods for 3DMP

3.3.3.6 Activity design

To complete the modeling and production of 3D objects, students need to go through four steps: sketch design; 3D modeling; Slicing and printing; Post printing processing and assembly. As shown in Figure 15.

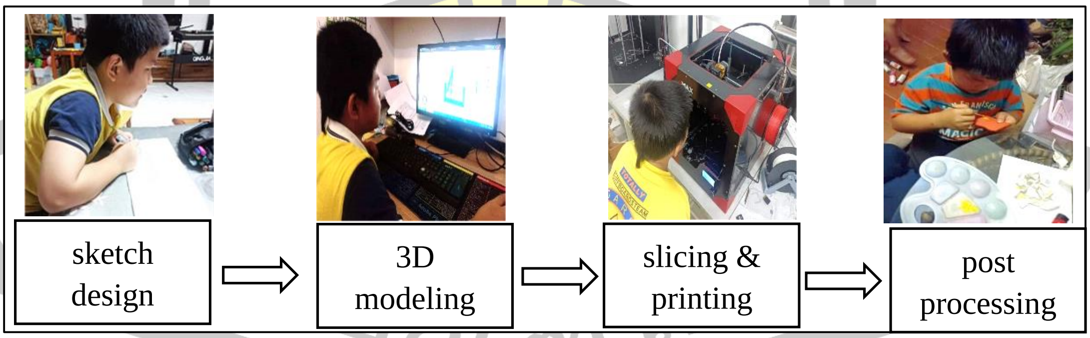


Figure 15 Activity flow

This course requires students to learn independently, which is reflected in several aspects. For students with a strong foundation, they can independently choose suitable 3D modeling software. The entire course follows a project-based learning approach, where each student is responsible for completing the entire process from design, modeling, printing, to the final product. Students are expected to learn new knowledge and skills by solving problems. For instance, during the modeling process, if they have questions about a specific operation, they can seek guidance from the teacher or classmates, or they can search the website community for relevant solutions or examples.

3.3.3.7 Assessment and Measurement

Assessment and Measurement: This refers to the assessment and measurement of students' level of completion in this course, using examination methods, including the quantity and quality of students' 3D modeling and 3D printing works.

3.4 Phase III Implementation and Monitoring

3.4.1 Population and Sample

The population are the students in Jiaying University. Jiaying University is a full-time public undergraduate university in Guangdong Province with a history of one hundred years of normal education. The university now has nearly 30,000 full-time students, covering 11 disciplines including literature, science, engineering, law and medicine.

In different tests, there are different samples. (1) In order to analyze the reliability of the test, a pilot-test was conducted before the quasi-experimental study. A physics teaching class (50 students) was selected to issue test questions, and 41 valid tests were collected. (2) In order to evaluate the spatial ability of students and provide a benchmark for the change of spatial ability before and after the implementation of the curriculum, a pre-test was conducted before the implementation of the curriculum. In order to assess spatial ability more accurately and expand the sample size, in addition to the students registered for the course, the students were invited to participate in the pre-test, and the students' classmates in the professional teaching class were also invited to participate in the pre-test. After screening the pre-test results, a total of 181 students' pre-test results were included in the analysis. (3) In order to conduct quasi-experimental research, a post-test was conducted on the students enrolled in the course. Since data from both pre-test and post-test are required for paired testing, student tests with valid data from both pre-test and post-test are included in the analysis. The results of 75 students were included in the matching analysis.

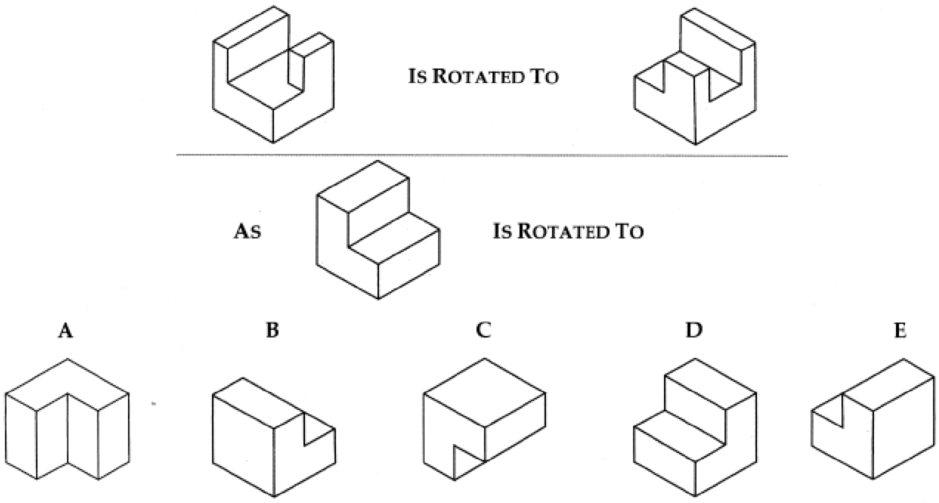
Due to the impact of COVID-19 and the fact that the study sample was in this school, this study has obtained approval (See Appendix B for details) from the Jiaying University Research Ethics Committee (Jiaying University Medical Ethics Committee). Volunteers will be informed in advance about this study and will have the option to consider whether to participate. They also have the right to change their mind and withdraw from this study at any time. Please refer to the attached documents for further information.

3.4.2 Instruments

Various instruments used to measure spatial ability were investigated for possible use in this study. The Purdue Visualization of Rotations Test (PVRT) was chosen. Other tests considered were the Sheperd-Metzler, Foam Board, Paper folding, and the Wheatley test (Sjolinder, 1998). An online test was investigated, but it was under development and not ready for use. Factors considered in choosing an instrument were content, appropriateness for the population, ease of administration and scoring, the amount of time required to administer the test, cost effectiveness, availability, availability of reliability data, and whether or not special training was required to administer the test.

The Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT: R) (Yoon, 2011) is a revised version of the PSVT: R (Guay, 1976). The Revised PSVT: R is an instrument to measure spatial visualization ability in 3-D mental rotation of individuals aged 13 and over. The psychometric instrument has 2 practice items followed by 30 test items that consist of 13 symmetrical and 17 asymmetrical figures of 3-D objects, which are drawn in a 2-D isometric format. In the revised version, figures are rescaled and items are reordered from easy to difficult under the framework of item response theory (IRT).

The Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT: R) was used for both the pretest and posttest. It is appropriate for use with adolescents and may be administered both in groups and individually. According to the test developers, Bodner & Guay (1997), this test is among the spatial tests least likely to be confounded by analytic processing strategies. The test was designed to measure the participants' ability to visualize the rotation of 3-dimensional objects. The instrument was chosen because of its high correlation with similar instruments measuring visualization that were not cost effective to use. The PVRT format used had 30 questions (Appendix C). In each question, an object was pictured in one position, and then it was shown in a second image, rotated to a different position. Participants were shown a second object and given five choices, one of which matched the rotation of the example object. They were asked to select the object that showed the same rotation as the example for that question. See Figure 16 for a sample question. The test is timed and students are given 15 minutes to complete the 30 test items.



You are to:

1. study how the object in the top line of the question is rotated;
2. picture in your mind what the object shown in the middle line or the question looks like when rotated in exactly the same manner;
3. select from among the five drawings (A, B, C, D, or E) given in the bottom line of the question the one that looks like the object rotated in the correct position.

Figure 16 Sample question from PSVT: R

3.4.3 Data collection

The questionnaire and PSVT: R have been converted into Chinese format and uploaded online. Students can complete the questionnaire and test online through their mobile phones. Therefore, relevant data can be collected easily. The figure below shows part of the data collection.

Figure 17 Data collection online

3.4.4 Curriculum Implementation

The instruction and course management of the 3D modeling and printing course are personally conducted by researchers. Location of instruction: Industrial Building, Jiaying University, Meizhou City, Guangdong Province, China. Course duration: March to December 2022, every Thursday during the 9th and 10th class periods. Target audience: All enrolled students. The course details are as shown in the following image.

Figure 18 Actual Implementation of the Course

3.5 Phase IV Analysis and Evaluation

3.5.1 Statistical Analysis

IBM-SPSS Statistics (version 26) was used for statistical analysis. During descriptive data analysis, the demographic information was used to check sample characteristics and reviewed for outlier identification. Although previous literature has shown that Revised PSVT: R has good reliability and validity, it is necessary to reanalyze the test due to differences in language and cultural backgrounds. The test results must conform to the normal distribution, which is the basis for subsequent analysis. The statistical methods for this study included independent samples t-test, paried samples t-test and analyses of variance (ANOVA, MANVOA) to test mean differences between/among groups for research questions. If the difference is significant, the effect size will be calculated. For independent sample t-tests, calculate the value of Cohen's d here.

3.5.2 Curriculum Assessment

This course is offered in accordance with the 'Jia Ying University General Elective Course Construction Standards' (see Appendix A for details). Before this course was offered, it underwent an application process and received approval from the school's expert panel. The course evaluation consists of three modules: student assessment, assessment materials, and teaching quality assessment.

CHAPTER IV

RESULTS

4.1 Result of Dialectical Analysis

The first stage of this study is dialectical analysis of the importance, necessity and feasibility of applying 3D modeling and 3D printing to improve the spatial ability of Chinese college students from two aspects of theory and literature analysis.

Firstly, at the theoretical level, the definition and characteristics of the dependent variable (spatial ability) and the independent variable (3D modeling and printing course) of this study are respectively expounded. Then, the supporting theory of improving spatial ability through 3D modeling and printing is systematically sorted out according to the characteristics, and the theoretical framework is designed. On the basis of literature review, this paper analyzes and synthesizes the historical development of spatial ability, the definition and connotation of spatial ability, the constituent elements and classification of spatial ability, the measurement methods and tools of spatial ability, and the differences and correlations of spatial ability. This paper discusses the possibility of improving spatial ability through literature research, and analyzes and lists various methods and ways to improve spatial ability. Relevant theories in the field of education that focus on 3D modeling and 3D printing to enhance spatial ability are cited and analyzed, including spatial cognitive theory, multimodal theory and multimodal learning, and cognitive development theory (constructivism). On the basis of explaining the concept, principle and process of 3D modeling and 3D printing, the integration of 3D modeling and 3D printing is analyzed in combination with the above related theories.

Secondly, at the literature analysis level, empirical research literatures on the application of 3D modeling and 3D printing to improve spatial ability are screened for analysis and classification. 3D modeling or 3D printing has indeed effectively improved the spatial ability of students in some empirical studies, so as to dialectically analyze the importance, necessity and feasibility of applying 3D modeling and 3D printing to improve the spatial ability of Chinese college students from another side.

The dialectical analysis of this study focuses on the importance, necessity and feasibility of 3D modeling and 3D printing courses for the improvement of spatial ability of college students. The following are the comprehensive results from the three levels of spatial ability, theoretical basis and empirical characteristics:

(1) Improvement of spatial ability

The study found that 3D modeling and 3D printing courses are important in significantly improving the spatial ability of college students. By participating in practical 3D modeling and 3D printing activities, students not only deepen their understanding of spatial concepts, but also develop their abilities in spatial imagination, rotation and transformation. This shows that the course has achieved substantial results in enhancing students' spatial thinking and cognitive level.

(2) Support of theoretical basis

The comprehensive application of constructivism, spatial cognition theory and multimodal theory provides a strong theoretical support for 3D modeling and 3D printing courses. Students learn within a theoretical framework, and verify the application of theory through practice, thereby deepening their understanding of spatial concepts. This proves the rationality of the theoretical basis for the design and implementation of this course, and provides theoretical guidance for improving students' spatial ability.

(3) Characteristics of 3D modeling and 3D printing

3D modeling and 3D printing, as technical means, provide strong support for the empirical effects of the course. Through practical operation, students not only learn the technical application, but also transform abstract concepts into entities, so as to have a deeper understanding of the concept of space. This highlights the feasibility of the course in improving students' spatial abilities, while showing that the technical features provide a solid foundation for the practical effects of the course.

(4) Comprehensive evaluation and suggestions

Based on the above results, this study concludes that 3D modeling and 3D printing courses have significant importance, necessity and feasibility in improving the spatial ability of college students. The course not only improves students' spatial ability through empirical activities, but also provides students with a systematic learning experience under the guidance of theoretical foundations. In order to further promote the research and practice in this field, we suggest that in the future teaching design, more attention should be paid to the organic combination of theory and practice, and interdisciplinary cooperation should be advocated to better cultivate the spatial ability of college students and meet the demand for comprehensive talents in the future society.

4.2 3D Modeling and Printing Course System

This study designed a complete and feasible 3D modeling and printing curriculum system, including standards, objectives, content, teaching strategies and assessment. First of all, at the beginning of the course design, the importance, necessity and feasibility of selecting 3D modeling and 3D printing as the main space of the course to improve the spatial ability of college students are demonstrated and analyzed, so as to establish the main space of the course. Secondly, in the course design, the preliminary analysis is carried out, including the demand analysis, requirement analysis and teaching environment analysis of students, schools and society. Thirdly, it adopts ADDIE curriculum design model and analyzes the principles of curriculum development. Finally, according to the actual situation of the school, a set of feasible curriculum system is developed. The Course system conforms to the "Jiaying University General Elective Course Construction Standards" (Appendix A). In addition to the conventional course materials, the course adopts a hybrid curriculum development model, combining the actual situation and curriculum characteristics, and innovative teaching strategies.

This course is offered in accordance with the 'Jia Ying University General Elective Course Construction Standards' (see Appendix A for details). Before this course was offered, it underwent an application process and received approval from the school's expert panel. The course evaluation consists of three modules: student assessment, assessment materials, and teaching quality assessment.

4.2.1 Student Assessment

This refers to the evaluation of student course performance, including the quantity and quality of 3D modeling models and the process and quality of 3D printed works. Model evaluation is done through a community website. After students create models, they upload them to the community website, where site administrators review the works. Works that pass the review, without modeling errors, are publicly displayed on the website and marked as excellent if applicable. The evaluation of students' printed works is done by the course instructor based on the aesthetics and complexity of the models. Some of the students' works are shown in the figures below.

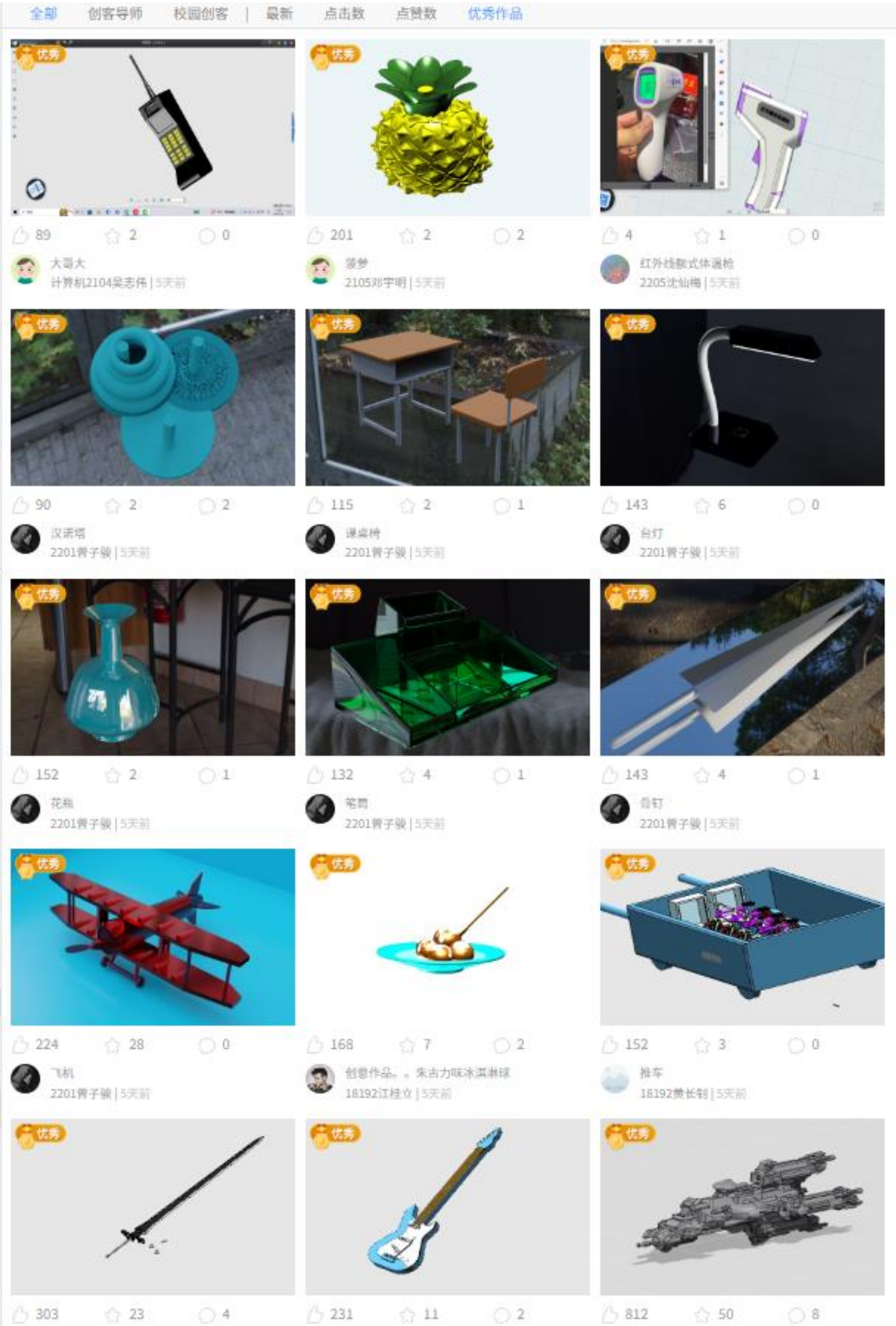


Figure 19 Part of Students' 3D Modeling Models

Figure 20 Part of Students' 3D Printed Works

4.2.2 Material Assessment

The material assessment for this course mainly focuses on the materials required for the development and implementation of the course. The specific list of materials is shown in the table below.

Table 10 Detail of Assessment Material

No.	Name of Material
1	Teaching Syllabus
2	Lecture Notes
3	Lesson Plans
4	Teaching Assignment Sheet
5	Teaching Calendar
6	Teaching Calendar Execution Results
7	End-of-Term Teaching Report

4.2.3 Teaching Quality Assessment

Teaching quality assessment is conducted by students to evaluate the overall course quality. There are a total of 15 evaluation criteria, each with different weights. Each criterion has five options: A (92 points), B (80 points), C (70 points), D (60 points), and E (50 points). Each enrolled student completes an evaluation form for teaching quality. The specific evaluation results are shown in the table below.

Table 11 Teaching Quality Assessment

No.	Evaluation Criteria	Weight	Score
1	Clear teaching objectives.	0.0625	90.462
2	The teaching content is substantial, with well-defined knowledge points, rich in information, and able to focus on the academic forefront of the subject.	0.0625	90.462
3	The depth and difficulty of the content are moderate, providing an appropriate amount of reference materials and guiding students in reading.	0.0625	89.282
4	The purpose and requirements of the practical aspects are clear; the practical projects are complete and in line with course requirements.	0.0625	89.897
5	There is good interaction between teaching and learning.	0.05	88.615
6	Teaching methods are appropriate, practical, and facilitate student understanding and application.	0.05	88.667
7	The teaching language is lively, easy to understand, and effective in addressing challenging points; it emphasizes fostering students' innovative thinking and abilities, encourages independent thinking, and pays attention to optimizing students' learning methods.	0.05	90.769
8	Homework and assessment methods are diverse, and timely grading and guidance are provided, with fair and reasonable evaluation.	0.05	89.231
9	The blackboard writing is concise, clear, and standardized, and various modern teaching methods are skillfully utilized.	0.025	89.333
10	Laboratory guidance is effective, and the teacher is proficient in solving problems that arise during student experiments.	0.025	89.436
11	The teacher is dedicated and enthusiastic about teaching; they treat students fairly and friendly while maintaining strict standards.	0.0625	88.615
12	The teacher has rich professional knowledge and teaching skills; they guide students patiently and tirelessly.	0.0625	89.231
13	The teaching language is accurate and standardized, with full teaching enthusiasm and a practical and confident teaching style that avoids empty talk.	0.0625	88.974
14	The teacher has strong organizational and communication skills, effectively managing and utilizing teaching time and space.	0.0625	90.205
15	Compared to other teachers, your overall evaluation of this teacher is:	0.25	89.846
Final Score		89.535	

From the table, it can be seen that students who took the course '3D Modeling and 3D Printing' gave an overall positive evaluation of various indicators. This is also reflected in some of the students' comments about the course, as shown in the table below.

Table 12 Some of Students' Comments

The teacher is serious and responsible in teaching, with lively and clear language, well-organized content, ample and appropriate examples. The teacher has strict requirements for students, encourages active participation in class, and creates a positive and enthusiastic classroom atmosphere.
Excellent, especially excellent teacher.
The teacher is very responsible, takes teaching seriously, and makes full use of teaching time and space.
Allows students to make good use of their time, very good.
Teacher Yang actively promotes our understanding of more related knowledge and guides our interests.
Respects the nature of each student; you are humorous, knowledgeable, and your teaching is well-structured with diverse classroom formats, rich and colorful content, leaving students with a lot to ponder.
The teaching language is lively, easy to understand, and excels in breaking through difficult points. The teacher values students' innovative consciousness and creative ability, encourages independent thinking, optimizes students' learning methods, and is dedicated and responsible for teaching. The teacher is fair and friendly to students while maintaining strict standards. The teacher has strong teaching organization and communication skills, effectively managing and utilizing teaching time and space.
The teacher is patient, meticulous, and the class content is rich, showing enthusiasm towards classmates.
The teacher's teaching is very attentive, with in-depth and clear explanations, making it easy for us to grasp key course concepts and improve our academic performance. The teacher's classroom management skills are excellent, creating a well-ordered learning environment where students are focused and attentive. Additionally, the teacher's personal qualities and educational experience are outstanding, enabling deep communication with students and attention to each student's individual development. We are very grateful for the teacher's dedication and care, and we will cherish the learning opportunities and work harder in our studies.

4.3 Evaluation of Chinese Undergraduates' Spatial Ability

4.3.1 Pilot-test Analysis

The Revised PSVT:R was translated from the English version to the Chinese version and was changed from a paper-based test to an online test. In order to ensure the quality of the test, a pilot test was conducted before the official distribution. The pilot test was administered to a specific class in the same school, majoring in optoelectronics (a STEM field). There was a total of 41 students in the class (24 males and 17 females), and all of them participated in the pilot test. From the analysis of the response rate, all pilot tests were completed successfully. The results of the pilot-test's relevant statistical analysis are as follows.

Table 13 Descriptive Statistics of Pilot-test

Variables	**Grouping**	**Count**	**Score**				**Time**			
			Mean	*Max*	*Min*	*SD*	*Mean*	*Max*	*Min*	*SD*
Gender	male	24	24	29	14	5	22.09	48.27	6.08	9.09
	female	17	19	26	7	5	28.01	52.40	4.20	14.77
Leading	a	17	24	29	14	5	20.82	35.20	10.62	6.64
	b	8	20	29	10	6	24.88	36.97	4.20	13.20
	c	6	22	27	14	5	31.51	52.40	14.60	16.94
	d	6	19	26	7	7	24.22	48.27	5.20	15.07
	e	4	21	23	18	2	29.76	49.17	15.30	14.23
Ranking	Last20%	2	29	29	28	1	27.43	35.20	19.67	10.98
	60%-80%	1	27	27	27		10.62	10.62	10.62	
	40%-60%	11	22	27	14	5	22.68	40.23	6.08	10.03
	20%-40%	14	20	26	10	4	25.47	52.40	4.20	15.22
	Top20%	13	23	29	7	7	25.75	46.98	5.20	10.49
Sport	a	0								
	b	1	27	27	27		26.67	26.67	26.67	
	c	16	23	29	14	5	25.58	52.40	6.08	14.90
	d	16	20	29	7	6	21.60	36.97	4.20	9.62
	e	8	23	29	14	5	28.09	49.17	17.47	10.40
Drawing	a	4	27	29	23	3	24.88	35.20	17.87	7.40
	b	9	21	29	7	7	25.12	48.27	5.20	14.92
	c	20	21	29	10	5	21.91	52.40	4.20	11.49
	d	6	25	27	22	2	31.07	46.98	17.47	12.00
	e	2	21	28	14	10	28.08	36.48	19.67	11.89

Variables	Grouping	Count	Score				Time			
			Mean	*Max*	*Min*	*SD*	*Mean*	*Max*	*Min*	*SD*
Egame	a	6	21	28	14	5	32.79	49.17	18.73	11.64
	b	5	15	24	7	7	15.91	34.70	4.20	12.56
	c	17	22	29	14	5	24.82	52.40	13.85	10.69
	d	9	26	29	23	2	23.66	48.27	10.62	12.90
	e	4	23	29	15	6	23.81	35.20	6.08	12.60
Art	a	8	25	29	18	4	27.32	48.27	15.30	11.60
	b	18	20	29	7	7	23.21	52.40	4.20	14.52
	c	14	22	28	14	5	24.64	46.98	14.60	9.28
	d	0								
	e	1	23	23	23		25.10	25.10	25.10	
Handwork	a	10	25	29	17	4	26.74	48.27	16.75	10.40
	b	17	20	29	7	7	23.48	52.40	4.20	13.31
	c	14	22	29	14	4	24.27	49.17	10.62	11.97
	d	0								
	e	0								

Note: a. Never; b. Rarely; c. Occasionally; d. Frequently; e. Always.

First, data from all subjects were considered for the reliability analysis. The Revised PSVT:R appeared to have good internal consistency (Cronbach's α = .851, N = 41). As shown in the following table, the values of the Cronbach's Alpha if Item Deleted ranged from .838 to .858. All 30 items appeared to be worthy of retention because removal of any of items would not significantly increase Cronbach's α.

Table 14 Cronbach's Alpha if Item Deleted

Items	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10
Cronbach's α	0.849	0.846	0.847	0.845	0.851	0.846	0.848	0.852	0.839	0.848
Items	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20
Cronbach's α	0.849	0.837	0.856	0.850	0.841	0.844	0.839	0.852	0.838	0.848

Items	Q21	Q22	Q23	Q24	Q25	Q26	Q27	Q28	Q29	Q30
Cronbach's α	0.842	0.839	0.844	0.849	0.849	0.848	0.840	0.845	0.847	0.858

4.3.2 Descriptive Statistics of Pre-test

Descriptive statistics of score and time are presented in the following table. The mean score of the 181 participants on the Re-vised PSVT: R was 18.98 with a standard deviation of 7.32. A total of 61.9% of participants scored above mean. The students' scores ranged from 3 to 30 and 4 students (2.21% of participants) achieved a perfect score of 30. The test time reported by 181 participants ranged from 45 to 8325 seconds with a mean of 1292. The test completion times of 4 perfect scorers ranged between 1177 and 3307 seconds with a mean of 2096 seconds.

Table 15 Descriptive Statistics of Score and Time

DV	N	Min	Max	Mean	Std. D	Skewness (Std. E)		Kurtosis (Std. E)	
Time	181	45	8325	1292.14	983.82	2.58	0.18	14.75	0.36
Score	181	3	30	18.98	7.32	-0.51	0.18	-0.82	0.36

Although the values of skewness and kurtosis show that the distribution of time and score does not conform to normality, the histograms (as shown in the follwing figure) that show a normal curve show that they conform to the distribution of a "bell-shaped curve ". Therefore, in many cases, it can still be detected by a normal distribution function.

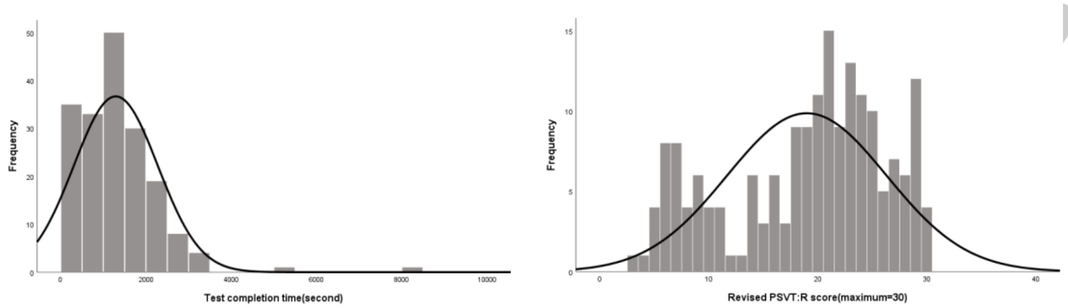


Figure 21 Histograms of time and score with normal curve

Participants' demographic profiles are presented in the following table. Descriptive statistics, such as means and standard deviations on the Revised PSVT: R and the test completion time, are presented by participants' characteristics, such as gender, academic major, etc.

Table 16 Students' performance by score and completion Time

Variables	**Grouping**	**Count**	**Time**		**Score**	
			Mean	Std. D.	Mean	Std. D.
Gender	Male	111	1117.71	600.33	20.11	7.25
	Female	70	1568.73	1350.51	17.20	7.13
Major	STEM	127	1258.96	741.07	19.95	7.06
	Non-STEM	54	1370.17	1404.56	16.70	7.49
Ranking	Last20%	18	1104.11	710.60	18.50	8.49
	60%-80%	28	1175.61	819.22	18.46	7.24
	40%-60%	41	1382.98	1285.60	19.07	6.87
	20%-40%	42	1481.36	1030.26	19.64	6.06
	Top20%	52	1195.52	823.01	18.83	8.38
Leader	Never	57	1102.56	610.86	20.02	7.47
	Rarely	33	1789.97	1601.56	18.67	6.88
	Occasionally	53	1323.74	857.85	19.04	7.33
	Frequently	21	962.29	784.31	15.43	7.54
	Always	17	1270.35	711.69	20.35	6.72
Sport	Never	2	781.50	378.30	18.00	0.00
	Rarely	20	1299.40	1197.45	19.00	7.20
	Occasionally	84	1352.33	1132.88	19.12	7.58
	Frequently	47	1171.09	588.91	19.45	6.71
	Always	28	1346.04	918.17	17.86	8.09
Drafting	Never	34	1068.76	636.59	18.18	7.84
	Rarely	46	1270.26	862.00	19.24	7.38

Variables	Grouping	Count	Time		Score	
			Mean	Std. D.	Mean	Std. D.
	Occasionally	66	1360.86	1147.59	19.27	6.78
	Frequently	20	1590.95	1176.59	21.05	7.28
	Always	15	1164.73	904.26	16.00	8.11
E-game	Never	9	1817.00	838.75	18.56	5.77
	Rarely	26	1151.04	933.69	16.62	7.63
	Occasionally	63	1235.13	760.88	19.90	6.96
	Frequently	54	1449.76	1307.46	19.94	7.05
	Always	29	1086.10	720.40	17.45	8.39
Art	Never	35	1041.77	680.80	17.97	7.76
	Rarely	52	1264.56	877.59	19.00	7.41
	Occasionally	57	1433.35	1187.68	19.25	6.74
	Frequently	22	1376.95	1077.61	21.55	7.96
	Always	15	1310.93	936.32	16.53	6.81
Handwork	Never	35	1079.57	716.96	18.17	8.08
	Rarely	63	1227.27	794.07	18.79	7.17
	Occasionally	66	1521.14	1247.95	20.61	6.60
	Frequently	9	1333.22	895.91	16.89	8.42
	Always	8	797.50	623.52	13.00	6.78

4.3.3 Correlation Analysis

The following table shows intercorrelations among the measures: The Revised PSVT: R score, test completion time, gender, major, leader, rank, sport, drafting, e-game, art, and handwork. Here the correlation coefficients were Spearman. Overall, the correlations among the observed variables ranged from -.32 to .69 and variance inflation factors as collinearity diagnostics ranged from 1.06 to 2.52, indicating no concerns of multicollinearity (Kline, 2011). The correlations of the Revised PSVT: R score with test completion time, gender, and major were statistically significant at the

p<0.01 level (2-tailed), with Spearman rho correlation coefficient, ρ_r=.57, -.21, and -.20 respectively. The correlations between time and gender were statistically significant at p<0.05 level (2-tailed), with Spearman rho correlation coefficient, ρ_r=.16.

Table 17 Correlations among the test and other demographic information

Variables	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
1. Time	--	.57**	.16*	-.04	.01	.04	.03	.08	-.05	.12	.08
2. Score		--	-.21**	-.20**	-.10	.04	-0.03	.01	.05	.05	.00
3. Gender			--	.13	.25**	.26**	-.03	.26**	-.32**	.18*	.13
4. Major				--	.13	-.08	.04	.10	.06	.22**	.09
5. Leader					--	.28**	.09	.24**	-.16*	.29**	.22**
6. Rank						--	.12	.13	-.30**	.01	-.02
7. Sport							--	.13	-.05	.01	.07
8. Drafting								--	-.17*	.69**	.56**
9. Egame									--	-.04	-.05
10. Art										--	.62**
11. Handwork											--

Note: ** Correlation is significant at the 0.01 level (2-tailed); * Correlation is significant at the 0.05 level (2-tailed)

4.3.4 MANOVA Analysis

Because of the correlation matrix (see the following table) among the four variables (Time and Score, Gender and Major), a two-way MANOVA was conducted to examine the unique effect of each variable by partially out the effect of the other variables. In Box's Test of Equality of Covariance Matrices for output results, p<0.001, indicates that the variance covariance matrix is not equal, so Pillai's Trace is used here. The interaction of gender and major had no statistically significant effect on the dependent variables (score and time), with F=1.525, p=.22, *Pillai's Trace*=.017, *partial* η^2=.017. The tests of between-subjects effects are shown in Table 4.6.

Multivariate analysis of variance shows gender was statistically significant for both score and time; Major was statistically significant for scores, but not for time.

Table 18 Results of two-way MANOVA

IV	DV	Multivariate Tests[a]			Tests of Between-Subjects Effects		
		Value	F	Sig.	df	F	Sig.
Gender	Time	0.17	17.907[b]	0.00	1.00	10.63	0.00
	Score				1.00	5.19	0.02
Major	Time	0.06	5.799[b]	0.00	1.00	0.23	0.63
	Score				1.00	6.27	0.01
Gender * Major	Time	0.02	1.525[b]	0.22	1.00	1.61	0.21
	Score				1.00	0.07	0.79

a. Design: Intercept + Gender + Major + Gender * Major
b. Exact statistic

Through the independent sample t-test after grouping, it was found that only among STEM major students, the gender difference in time is statistically significant, with $t(61.37)=-2.03$, $p=.046$. In terms of time, male students ($M=1149.40$, $SD=588.47$) outperformed female students ($M=1465.64$, $SD=939.13$) with a mean difference of -316.24, and the Levene's test $F=19.46$, $p<0.01$.

4.3.5 Gender and Major Difference

For gender and academic major, they belong to two categorical variables. The score and time were compared by independent sample t-tests. The results are shown in the following table.

Table 19 Independent Samples T Test for gender and major

DV	IV	Levene's Test		t-test			Cohen's d
		F	Sig.	t	df	Sig.	
Time	Gender	27.17	0.00	-2.64	86.43	.01	.47
	Major	8.37	0.00	-0.55	65.90	0.58	
Score	Gender	0.20	0.66	2.65	179	.01	.40

Major	1.43	0.23	2.78	179	.01	.45

In terms of score, male students (*M*=20.11, *SD*=7.25) outperformed female students (*M*=17.20, *SD*=7.13) with the mean difference of 2.91 on the Revised PSVT: R, with *t* (179) =2.65, *p*<.05, Cohen's *d* =.40. STEM students (*M*=19.95, *SD*=7.06) outperformed non-STEM students (*M*=16.70, *SD*=7.50) with the mean difference of 3.25 on the Revised PSVT: R, with *t* (179) =2.78, *p*<.05, Cohen's *d* =.45.

In terms of time, female students spent 451.02 seconds more than male students on average, showing a statistical difference in test completion time between the two genders with *t* (83.43) = −2.64, *p* = .01, Cohen's *d* = 0.47. On average, STEM students spent 111.21 seconds less than non-STEM students, but there is no significant statistical significance in competition time with *t* (65.90) = -.55, *p*=.58.

4.3.6 Test Score and Time

Because score and time are both continuous variables, to further explore their relationship, scores are divided into three levels: 1(0-10), 2(11-20), and 3(21-30). Use the graded score as a new variable and perform a one-way ANOVA analysis with time. The results showed that: level 3 (M=1590.38, SD=734.33) students spent 117.83 seconds more than level 2 (M=1472.55, SD=1198.89) on average, but there is no significant statistical significance in competition time with p=.42; level 3 students spent 1326.02 seconds more than level 1(M=264.36, SD=265.93) students on average, showing statistical difference with p<0.001; level 2 spent 1208.19 seconds more than level 1 students, also showing statistical difference with p<0.001.

4.4 Effect of Spatial Ability Improvement

The enrollment numbers for two semesters were 52 and 53, respectively. A preliminary analysis and screening of the collected test results were conducted, and invalid test records were removed. The criteria for invalid records were as follows: ① Records with only pre-test or only post-test results; ② Records with a repetition rate of answers (e.g., the percentage of selecting option C) reaching or exceeding 90% (27/30) in the 30-item test; ③ Records with a test duration of less than 100 seconds. After screening, a total of 75 records were included in the analysis, accounting for 71.43% of the total enrollment.

4.4.1 Normality Testing

When conducting a paired t-test, it is essential to focus on the normality of the differences (pre/post-test variations) rather than the individual normality of the pre-test and post-test data. Typically, the distributions of the pre-test and post-test data do not necessarily need to independently satisfy normality assumptions. However, the distribution of the differences (i.e., the gain variable) should approximate a normal distribution since the paired t-test relies on the assumption of normality for the differences(Field, 2018). Therefore, in the process, an additional variable "Gain" was introduced for normality testing. Descriptive statistics for the pre/post-test differences are presented below. As can be seen, the distribution of the pre/post-test differences closely approximates a normal distribution with a Skewness index of -.19 and a Kurtosis index of .99. This can also be confirmed from the histogram below, which includes a normal curve.

Table 20 Descriptive Statistics of Gain

	N	Min	Max	Mean	Std. D	Skewness (Std. E)		Kurtosis (Std. E)	
Gain	75	-20	15	1.64	6.379	-0.190	0.277	0.991	0.548

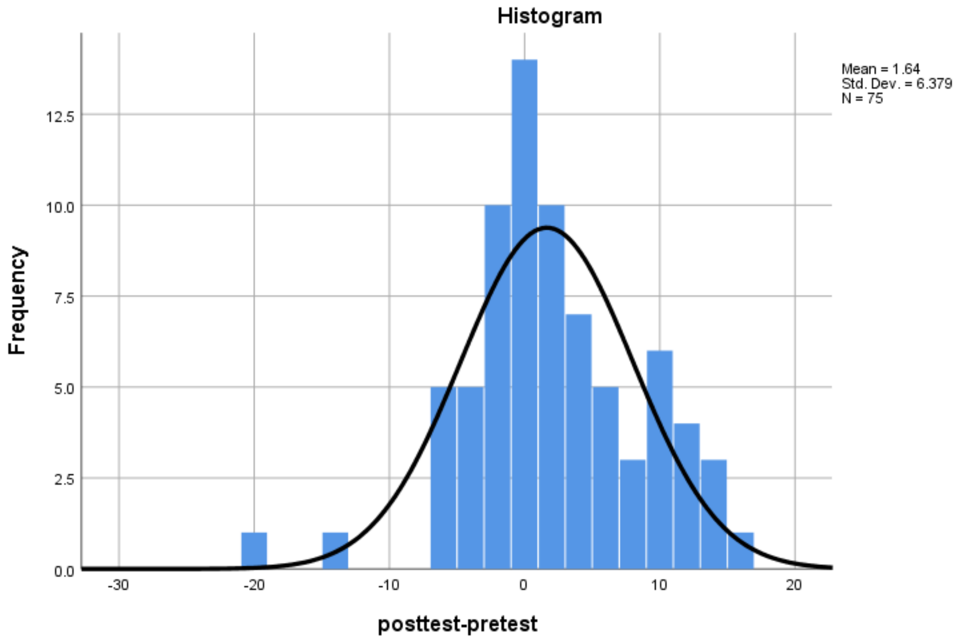


Figure 22 Histogram of Gain

4.4.2 Descriptive Statistics

The descriptive statistics for the test scores, test time, and the differences in pre-post test scores for 75 participants are shown in the table below. Among them, in the pre-test and post-test, 3 students each scored full marks, accounting for 4%. Regarding the differences in pre-test and post-test scores, 29 students' scores decreased, representing 38.7% of the total; 7 students' test scores remained the same, accounting for 9.3%; and 39 students' scores improved, making up 52%.

The pre-test had an average score of approximately 19.43, with a minimum score of 6 and a maximum score of 30. The skewness is -0.26, indicating a slight leftward skew in the distribution, while the kurtosis is -1.24, suggesting a relatively flat distribution.

For the post-test, the average score was approximately 21.07, with a minimum score of 5 and a maximum score of 30. The skewness is -0.71, suggesting a slight leftward skew, while the kurtosis is 0.57, indicating a distribution that is close to normal.

Table 21 Descriptive Statistics of Pre-post Test

DV	N	Min	Max	Mean	Std. D	Skewness (Std. E)		Kurtosis (Std. E)	
Pretest	75	6	30	19.43	7.24	-0.26	0.28	-1.24	0.55
Posttest	75	5	30	21.07	5.71	-0.71	0.28	0.57	0.55
Gain	75	-20	15	1.64	6.38	-0.19	0.28	0.99	0.55

More detailed demographic statistics of the participants are presented in the table below. Descriptive statistics, such as the mean and standard deviation of the revised PSVT:R and the test completion time, are derived based on participant characteristics, such as gender, academic major, and spatial experience. This table provides descriptive statistics for various variables related to pre-test, post-test, time, and differences in scores, categorized by different groups such as major, gender, leading style, ranking, sport, drawing, E-game, art, and handwork. The table provides a comprehensive overview of the descriptive statistics for each group within the specified variables. This information allows for an understanding of the central tendency, variability, skewness, and kurtosis of the data in different subgroups, which can be valuable for further analysis and interpretation in next research.

Table 22 Descriptive Statistics of Pre-post Test

Variables	Grouping	Count	Pretest		Posttest		Gain	
			Mean	*SD*	Mean	*SD*	Mean	*SD*
Major	STEM	48	20	7	22	6	2	6
	Non-STEM	27	18	8	20	5	2	7
Gender	male	48	20	7	21	6	1	7
	female	27	18	7	21	5	3	5
Leading	a	18	19	8	20	7	1	6
	b	14	20	5	20	5	1	6
	c	31	21	7	22	6	1	7
	d	5	11	4	18	5	7	7
	e	7	21	7	24	4	4	4

Variables	Grouping	Count	Pretest		Posttest		Gain	
			Mean	*SD*	Mean	*SD*	Mean	*SD*
Ranking	Last20%	9	20	8	19	7	0	9
	60%-80%	15	19	8	19	6	1	8
	40%-60%	18	19	7	20	6	1	5
	20%-40%	15	20	8	23	4	3	7
	Top20%	18	20	7	23	5	3	4
Sport	a	1	6	.	18	.	12	.
	b	10	18	5	23	3	5	6
	c	37	21	7	21	6	0	6
	d	16	21	7	22	5	1	5
	e	11	16	9	19	7	3	10
Drawing	a	16	18	7	19	5	1	7
	b	19	20	6	23	5	3	5
	c	25	20	8	21	7	1	6
	d	9	23	7	25	4	1	5
	e	6	15	8	18	7	2	12
Egame	a	2	20	7	18	5	-2	2
	b	8	19	9	24	3	4	7
	c	25	20	8	23	5	3	6
	d	24	18	6	19	5	1	5
	e	16	21	7	20	7	0	8
Art	a	11	19	6	18	5	-1	6
	b	13	21	7	23	4	3	5
	c	28	18	8	20	6	2	6
	d	16	22	6	25	4	3	6
	e	7	19	9	18	7	0	11
Handwork	a	10	19	6	20	6	1	5
	b	24	20	7	21	5	1	6

Variables	Grouping	Count	Pretest		Posttest		Gain	
			Mean	*SD*	Mean	*SD*	Mean	*SD*
	c	33	19	8	22	6	2	6
	d	4	20	7	21	5	1	6
	e	4	16	10	16	7	-1	15

Note: a. Never; b. Rarely; c. Occasionally; d. Frequently; e. Always.

4.4.3 Analysis of Overall Improvement in Spatial Ability

A paired sample t-test was conducted to analyze the scores and time before and after the intervention, and the results are presented in the table below. In Pair 1, we compared the differences in scores between the pre-test and post-test. The results indicate that the average score difference is 1.64, with a 95% confidence interval ranging from 0.17 to 3.11. The t-value is 2.23, with a corresponding two-tailed significance level (Sig.) of 0.03, indicating that the post-test scores are significantly higher than the pre-test scores.

Table 23 Spatial Ability Improvement Effect Paired T-test

		Mean	SD	SEM	95% CI		*t*	*df*	*p*
					Lower	Upper			
Pair-test	Posttest - Pretest	1.64	6.38	0.74	0.17	3.11	2.23	74	0.03

4.4.4 Analysis of Spatial Ability Improvement Effect by Category

4.4.4.1 Analysis of Improvement Effects in Different Major

First, students' majors are categorized. STEM majors, such as physics, chemistry, computer science, biology, geography, and civil engineering, are grouped into STEM (*n*=48), while other majors like social sciences, economics, and arts are grouped into non-STEM (*n*=27). Independent t-tests were conducted on the pretest and posttest results of students from different majors, and the results are presented in the table below. In the pretest, STEM students scored higher (20.13±7.02) compared to non-

STEM students (18.19±7.59). In the posttest, STEM students' scores (21.75±5.81) were higher than those of non-STEM students (19.85±5.44). However, there were no significant differences in spatial ability test scores between students of different majors, both in the pretest and posttest.

Table 24 Independent T-tests with Major of Pre-post Paired

	Levene's Test		**t-test for Equality of Means**						
	F	*Sig.*	*t*	*df*	*p*	*MD*	*SE(d)*	95% CI Lower	95% CI Upper
Pretest	0.09	0.77	1.12	73.00	0.27	1.94	1.74	-1.52	5.40
Posttest	0.04	0.84	1.39	73.00	0.17	1.90	1.37	-0.82	4.62

Paired t-tests were conducted on the pretest and posttest results of students from different majors, and the results are presented in the table below. In terms of spatial ability test scores, STEM students' improvement (1.63±6.28) was slightly lower than that of non-STEM students (1.67±6.68), but the difference in improvement was not statistically significant (p>.05).

Table 25 Paired T-tests of Improvement Effects in Different Major

Grouping	**Pair**	**Mean**	**SD**	**SEM**	**95% CI** Lower	**95% CI** Upper	*t*	*df*	*p*
STEM	Posttest - Pretest	1.63	6.28	0.91	-0.20	3.45	1.79	47	0.08
Non-STEM	Posttest - Pretest	1.67	6.68	1.29	-0.98	4.31	1.30	26	0.21

4.4.4.2 Analysis of Gender Differences in Improvement Effects

An analysis was conducted on the test results of students of different genders to explore gender differences in spatial ability levels and improvement effects specifically for the Revised PSVT:R test. Students were grouped by gender (48 males and 27 females), and independent t-tests were performed on the pretest and posttest results. The results are presented in the table below. In the pretest, male students scored higher (20.17±7.16) than female students (18.11±7.32). However, in the posttest, male students' scores (21.02±6.21) were lower than those of female students (21.15±4.83). Nevertheless, there were no statistically significant differences in spatial ability test scores between students of different genders, both in the pretest and posttest (p>0.5).

Table 26 Independent T-tests with Gender of Pre-post Paired

	Levene's Test		**t-test for Equality of Means**						
	F	*Sig.*	*t*	*df*	*p*	*MD*	*SE(d)*	95% CI Lower	95% CI Upper
Pretest	0.02	0.88	1.18	73.00	0.24	2.06	1.74	-1.41	5.52
Posttest	0.38	0.54	-0.09	73.00	0.93	-0.13	1.38	-2.89	2.63

A paired t-test was conducted to analyze the gender differences in the changes in spatial ability before and after the course implementation. The results are presented in the table below. In terms of spatial ability test scores, female students showed a significant improvement effect (3.04±5.49), which was statistically significant (p=0.01<0.05). On the other hand, male students exhibited an improvement in spatial ability, but the improvement effect (0.85±6.75) was not statistically significant (p=0.39>0.05).

Table 27 Paired T-tests of Improvement Effects with Gender

Grouping	**Pair**	**Mean**	**SD**	**SEM**	**95% CI Lower**	**95% CI Upper**	***t***	***df***	***p***
Female	Posttest - Pretest	3.04	5.49	1.06	0.86	5.21	2.87	26	0.01
Male	Posttest - Pretest	0.85	6.75	0.97	-1.11	2.82	0.88	47	0.39

4.4.4.3 Analysis of Improvement Effects in Different Spatial Experience

To analyze the effectiveness of the course in improving spatial abilities among students with different spatial experiences, the scores of three variables (Drawing, Art, Handwork) were summed to create a new variable called "SExp". Since this variable is continuous, linear regression was used to examine whether there are differences in spatial ability improvement among students with varying spatial experiences. The dependent variable used is "Gain," which represents the change in spatial abilities between pre-test and post-test. The results of the linear regression are presented in the following table. In this model, the regression coefficient for "SExp" is 0.042, indicating that for each unit increase in spatial experience, there is a 0.042 unit increase in "Gain." However, the significance level (Sig.) of the regression coefficient is greater than 0.05, indicating that the impact of "SExp" on "Gain" is not statistically significant. In summary, based on the results of this linear regression model, it can be concluded that students' spatial experience does not have a significant impact on changes in spatial ability.

Table 28 Linear Regression Analysis of Spatial Experience on Improvement Effects

	Unstandardized Coefficients		Standardized Coefficients	*t*	*Sig.*
	B	Std. Error	*Beta*		
(Constant)	1.30	2.18		0.60	0.55
SExp	0.04	0.25	0.02	0.17	0.87

4.4.4.4 Analysis of Improvement Effects in Different Spatial Ability Levels

To analyze the differences in spatial ability improvement among students with different levels of spatial ability after the course implementation, students were divided into three groups based on their pre-test spatial ability scores (*n*=75, *M*=19.43, *SD*=7.24): high, medium, and low. A paired samples t-test was conducted between the low-score group (*n*=26, *M*=11.00, *SD*=2.91) and the high-score group (*n*=20, *M*=27.80, *SD*=1.40) to determine if there were significant differences in pre-test and post-test scores within these two groups. The results of the test are presented in the table below.

Table 29 Paired T-tests of Improvement Effects in Different Spatial Ability Levels

Groups	Pair	Mean	SD	SEM	95% CI		*t*	*df*	*p*
					Lower	Upper			

Groups	Pair	Mean	SD	SEM	95% CI		*t*	*df*	*p*
Low	Posttest - Pretest	6.88	5.91	1.16	4.50	9.27	5.94	25	0.00
High	Posttest - Pretest	-2.75	5.07	1.13	-5.12	-0.38	-2.43	19	0.03

The mean difference between post-test and pre-test scores for students in the low spatial ability group is 6.88 points higher. This positive value indicates that, on average, students in this group improved their spatial ability scores after the course implementation. The mean difference between post-test and pre-test scores for students in the high spatial ability group is -2.75. This negative value suggests a slight decrease in scores, on average, after the course implementation. In summary, for students with low spatial ability, there was a significant improvement in spatial ability scores, accompanied by an increase in the time taken to complete the test. However, for students with high spatial ability, there was a significant decrease in spatial ability scores, with no significant change in test completion time.

4.4.4.5 Analysis of Improvement Effects with Other Factors

Since other statistical characteristics (Leading, Sport, Ranking) of students were assessed using Likert scales, a correlation analysis was conducted between the change (Gain) in spatial ability before and after the test and these characteristics. The results of the correlation analysis are shown in the table below. From the results, it can be observed that whether students frequently hold leadership positions, engage in regular physical activity, and their overall ranking in assessments are not significantly correlated with changes in spatial ability.

Table 30 Pearson Correlation Between Improvement Effects and Other Factors

		Gain	Leading	Sport	Ranking
Gain	Pearson Correlation	1	0.16	-0.09	0.18
	Sig. (2-tailed)		0.16	0.42	0.13

CHAPTER V

CONCLUSION AND DISCUSSION

5.1 Conclusion

5.1.1 3D Modeling & Printing as Important Means to Improve Spatial Ability

This study dialectically analyzes the importance, necessity and feasibility of 3D modeling and 3D printing courses to improve college students' spatial ability from three aspects: spatial ability, theory (constructivism, spatial cognition theory, multimodal theory) and demonstration, and the characteristics of 3D modeling and 3D printing. Through the design and implementation of 3D modeling and 3D printing courses, this study makes an in-depth analysis from three aspects: spatial ability, theoretical basis and technical characteristics. The following are our conclusions on the importance, necessity and feasibility of this course to improve the spatial ability of college students:

(1) Improvement of spatial ability

The results clearly show that 3D modeling and 3D printing courses play a key role in improving the spatial ability of college students. Through theoretical study and practical operation, students have made significant progress in spatial cognition, multimodal understanding and constructivism learning. This is reflected not only in their deeper understanding of the form and structure of objects, but also in their creative thinking in three-dimensional design.

(2) Support of theoretical basis

The curriculum uses constructivism, spatial cognitive theory, and multimodal theory as theoretical foundations, which provide students with a framework for in-depth understanding and application of spatial concepts. Constructivist learning styles encourage students to construct knowledge through practical experience, while spatial cognition theory and multimodal theory emphasize the importance of understanding space through multiple senses and ways. The comprehensive application of these theories provides a solid theoretical foundation for the successful implementation of the curriculum.

(3) Characteristics of 3D modeling and 3D printing

The characteristics of 3D modeling and 3D printing provide strong support for the empirical effects of the course. Through the process of 3D modeling, students not only exercised their spatial imagination, but also cultivated their problem-solving and innovation abilities. 3D printing technology transforms abstract designs into entities, enhancing students' practical understanding of spatial concepts. This empirical feature enables students to find a balance between creativity and practicality and improves their comprehensive ability.

(4) Comprehensive evaluation of importance, necessity and feasibility

Based on the analysis of the above three aspects, we conclude that 3D modeling and 3D printing courses are important, necessary and feasible in improving the spatial ability of college students. With the support of the theoretical basis and the empirical effect of the characteristics, this course not only expands the students' spatial cognitive ability, but also promotes the comprehensive learning across disciplines. In the current era of rapid development of science and technology, it is particularly urgent to train students to have this kind of spatial ability. Therefore, we strongly recommend that similar courses be promoted and applied more widely in higher education.

5.1.2 3D Modeling and Printing Course System

In this study, by integrating emerging technologies such as three-dimensional modeling and 3D printing, and based on the need to enhance the spatial abilities of university students, a blended learning course development model was applied to develop a "Three-Dimensional Modeling and Printing" course system. Through the implementation of the course and the analysis of the results presented earlier, it is evident that this course indeed effectively improves the spatial abilities of undergraduate students. The assessment of the course reveals that it has a comprehensive curriculum structure, and students have experienced multifaceted development through this course. The teaching evaluations are positive, highlighting its significant practical value.

(1) The effectiveness of the curriculum system

After field testing and feedback from students, we found that the designed 3D modeling and printing course system has achieved remarkable results in improving the spatial ability of college students. Students not only learn practical 3D modeling and printing skills through the course, but also make significant progress in spatial thinking, creative problem solving and teamwork.

(2) Display of learning results

Through the presentation and assessment of students' work, we see the practical impact of the course. Students were able to transform abstract concepts into concrete three-dimensional models and materialize their creative ideas through printing. This not only improves their spatial cognition ability, but also exercises their design and implementation ability.

(3) Advantages of interdisciplinary integration

The design of this curriculum system takes into account the importance of interdisciplinary integration. By incorporating knowledge from areas such as engineering, art and design into the curriculum, we find it easier for students to understand and apply what they learn. This comprehensive learning approach provides them with a broader perspective and helps to develop interdisciplinary thinking and comprehensive abilities.

(4) Influence on college students' career development

Ultimately, through a follow-up survey of students, we found that students who participated in 3D modeling and printing courses were more competitive in terms of career development. They not only have a deeper accumulation in the field of technology, but also show a stronger innovation ability and team spirit, laying a solid foundation for their future careers.

(5) Implications for future research

Finally, this study provides useful enlightenment for the future research in the field of spatial ability cultivation of college students. We encourage further in-depth study of student groups at different levels and majors to gain a more complete understanding of the impact of 3D modeling and printing courses on spatial ability. At the same time, different variants of the curriculum system can be explored to meet the needs of different disciplines and teaching environments.

To sum up, the design and implementation of 3D modeling and printing course system is of great significance to improve the spatial ability of college students. This curriculum system provides a feasible educational program for cultivating students' innovative thinking, practical ability and comprehensive accomplishment. We hope that this study will provide valuable references for educators, policy makers and researchers to promote the development of spatial competence training in college students.

5.1.3 Assessment of Spatial Ability in Chinese University Students

In order to investigate the current levels of spatial abilities among Chinese university students, analyze differences in spatial abilities, and identify related influencing factors, this study expanded its sample size during the early stages of the "3D Modeling and Printing" course implementation. Alongside the implementation of the Revised PSVT:R, a demographic survey was conducted.

Correlation analysis showed that test scores and test time, gender and major of students were significantly correlated ($p<0.01$), and test time and gender were also significantly correlated ($p<0.05$). Test scores and test time have little correlation with other factors (Ranking, Leader, Sport, Drafting, Egame, Art, and Handwork). In Maeda & Yoon's study (Maeda & Yoon, 2012), at least five distinguishable factors were proposed to explain the cause and extent of these gender differences, which were labeled as biological, strategic, experiential, affective, and test administration factors. These factors interact with each other, and are finally reflected in the gender difference in spatial ability. In this study, Variables (Major, Ranking, Leader, Sport, Drafting, Egame, Art, and Handwork) can be attributed to experience factors, while test time (test without time limit) is attributed to test administration factors. In the research results, the correlation between spatial ability and these factors can be explained as follows:

(1) Spatial ability and Ranking, Leader: Ranking refers to the ranking of students' comprehensive examination, which is the investigation of a student's comprehensive ability, not just the examination score of a certain subject. Therefore, the correlation between spatial ability and Ranking is not strong. In other words, spatial ability only explains part of Ranking. Similarly, there is no direct correlation between students' spatial ability and leadership

(2) Spatial ability and Sport: Tartre (Tartre, 1990) believes that spatial ability consists of two distinct components: spatial visualization and spatial orientation. The Revised PSVT: R mainly tests spatial visualization, while the students' motor ability is mainly related to spatial orientation. So, in this research, spatial ability is not strongly correlated with sport.

(3) Spatial ability and Drafting, E-game, Art, Handwork: The size of the gender difference in spatial ability may be attributed to the amount of a person's previous spatial experience, that is, spatial ability can be developed through activities involving

spatial tasks (Feng & Pratt, 2007). Past research found that some activities related to spatial tasks may be more common among boys than girls, such as playing computer and/or electronic games (Cherney, 2008; Feng et al., 2007; Quaiser-Pohl et al., 2006), or playing with construction toys such as Lego® or building blocks (Deno, 1995). These activities provide boys with more spatial experience than girls, which may contribute to boys' advantage in spatial tasks. However, no statistically significant association was found in this study. Possible reasons include: insufficient sample size (for example, the variable Handwork has a sample gap of more than 4 times between groups); the scale is unreasonable and cannot be investigated well and reflect the situation of students.

Further analysis shows that, in the spatial test scores, males were significantly higher than females; STEM was significantly higher than non-STEM students. Males were significantly faster than females in spatial test speed; STEM was faster than non-STEM students, but not statistically. Through two-way MANOVA analysis, there is no statistical significance for the interaction of gender and major on test score and time. Through the independent sample t-test after grouping, it was found that only among STEM major students, males tested significantly faster than females.

In a meta-analysis by Maeda and Yoon(Maeda & Yoon, 2012)integrating 70 PSVT: R effect sizes from 40 major studies measuring gender differences in mental rotation ability, male participants outperformed females on the test (Hedges' g=.57). The result of this study (Cohen's d=.40) was similar to it, and the effect size is moderate. Understanding gender differences in spatial ability has been an issue posed by psychologists and educational researchers since the early history of spatial ability research. In particular, among studies of different subfactors of spatial ability, studies focusing on mental rotational ability provide consistent evidence for gender differences in favor of males. While this trend seems clear, the extent of the gender difference varies across studies.

The results indicated that STEM students outperformed non-STEM on the test score (Cohen’s d=.45). Past research shows that strong spatial abilities are necessary for success in multiple technical and scientific fields, and there is a link between performance in STEM-related courses and spatial ability, and accordingly, students with better spatial ability are more likely to choose STEM major. At the course level, science, mathematics, and computing courses in STEM fields, as well as technical courses with substantial drawing or computer graphics components, can significantly improve students' spatial ability.

The interaction of gender and major was not statistically significant, suggesting that these two variables were not moderators of students' spatial performance. This is inconsistent with the results of some current studies, e.g., (Sharobeam, 2016), possibly due in part to the small sample size. In addition, the assessment was a quasi-experimental survey, and the test samples were students who chose the course "3D Modeling and Printing", and the students who chose this course tend to have differences in spatial ability, which affects the survey results.

While the literature on gender differences in mental rotation processing speed has conflicting results (Jansen-Osmann & Heil, 2007; Scali et al., 2000), in this study there were significant gender differences in test completion time (males faster than females). The analysis results show that there was a positive moderate correlation between spatial test completion time and score. one-way ANOVA analysis results showed that students who spent more time on spatial tests tended to score higher than those who did not, and after a certain amount of time, the increase in scores was not significant. On the other hand, males scored significantly higher than females on the test. Therefore, the spatial ability test also reflects the students' sincere attitude to a certain extent. Due to the use of online testing and the wide range of test completion times, it is reasonable to infer that not all students attempted all questions. Therefore, although this test eliminates the risk of missing a student with great spatial talent, it also creates the risk of misjudgment due to the results of not carefully evaluating the test in the analysis.

5.1.4 3D Modeling and Printing Course Enhances Spatial Ability

5.1.4.1 Course Significantly Improved College Students' Spatial Ability

Before and after the course implementation, students were subjected to Revised PSVT: R test, and their spatial ability test results were subjected to paired-sample t-tests. The results showed that there was a significant difference in the numerical values of spatial ability before and after the course for 75 undergraduate students (t=2.23, p=0.03<0.05), with an improvement of 1.64 in the post-test compared to the pre-test. This indicates that the "Three-Dimensional Modeling and Printing" course significantly improved the spatial abilities of undergraduate students. This also confirms that spatial abilities can be significantly enhanced through practice and training. Moreover, the integration of emerging technologies such as three-dimensional modeling and 3D printing, through the offering of independent courses, is an effective and feasible way to enhance the spatial abilities of undergraduate students.

During the 3D modeling process, learners can freely rotate and manipulate objects, changing the perspective and distance of objects, thereby enhancing their understanding of three-dimensional rotations. The experience of rotating three-dimensional objects and changing the perspective and distance of objects in 3D space helps students mentally rotate visual stimuli in the PSVT: R test, imagining the entire process of visual stimuli rotating in three-dimensional space around themselves. The process of rotating objects in 3D modeling reveals the hidden three-dimensional information of objects, helping learners construct complete mental models and enhance their spatial perception, thereby improving their spatial visualization abilities. When students print their 3D modeling creations into physical models, this tangible model printing sparks their interest and transforms learning from an initial visual medium to "visual medium + tactile medium." According to information processing theory, humans perceive the world through a variety of sensory stimuli, and the diversity of stimuli enhances the stability of knowledge. The three-dimensional concepts and modeling skills acquired by learners during the process of freely rotating and touching physical models contribute to their conversion of working memory into long-term memory. When faced with tests and problems, they can retrieve this experience, mentally visualize the full rotation of objects in their brains, and thus demonstrate a higher level of mental rotation ability.

5.1.4.2 Differential Improvement Effects of Spatial Ability

By analyzing the specific effects of the course on the improvement of students' spatial abilities and delving into the differences and principles of enhancing spatial abilities through the course, we have conducted a series of paired-sample t-tests to examine the differential effects of the Three-Dimensional Modeling and Printing course on spatial abilities. The results indicate significant differences in the improvement of spatial abilities for students with different spatial ability levels and genders. In other aspects, such as different majors and levels of spatial experience, the improvement in spatial abilities, while varying, is not statistically significant.

(1) Improvement in Spatial Abilities for Students from Different Majors and Backgrounds.

To determine if there are significant differences in the improvement of spatial abilities among students with different academic backgrounds, the researchers divided enrolled students into STEM and non-STEM majors and conducted paired-sample t-tests on their spatial abilities before and after the course. The results show that students from both STEM and non-STEM majors experienced improvement in spatial abilities. In terms of improvement, STEM students' improvement (1.63±6.28) was slightly lower than that of non-STEM students (1.67±6.68), but the difference in improvement was not statistically significant (p>.05). In the linear regression analysis of spatial experience and spatial improvement gain, the results indicate that, students' spatial experience does not have a significant impact on changes in spatial ability (B=0.04, t=0.17, p=0.87).

Generally, STEM students and students with higher spatial experience have more opportunities to engage with spatial problems, according to Piaget's previous research perspective. It was expected that STEM students and students with higher spatial experience would show better improvement in spatial abilities. This expectation has also been supported by empirical research in some literature. However, the results of this study do not align with this expectation. One possible explanation is that the implementation of this course has bridged the gap in opportunities to engage with spatial problems caused by differences in majors and backgrounds among students. Spatial abilities improved for students from different majors, with non-STEM students experiencing a greater improvement in spatial abilities. This further confirms that the "Three-Dimensional Modeling and Printing" course effectively enhances the spatial abilities of undergraduate students. As mentioned earlier in the theory, the multimodal nature of three-dimensional modeling and 3D printing technologies, tools, and processes plays a crucial role in enhancing students' spatial abilities, addressing the limited exposure to spatial problems in other coursework tasks.

(2) The Impact of the Course on Students with Different Levels of Spatial Abilities.

Paired-sample t-tests for pre and post-tests for students with different levels of spatial abilities showed that the low-scoring group had a significant improvement in spatial abilities ($t = 5.94$, $p < 0.01$), while the high-scoring group showed a significant difference between pre and post-tests ($t = -2.43$, $p = 0.03$), with a decline in post-test scores. This suggests that the "Three-Dimensional Modeling and Printing" course is more effective in developing the spatial abilities of students with weaker spatial skills. This finding does not support the research conclusion of Huk (Huk, 2006), which suggests that the use of 3D models increases the cognitive load for students with lower spatial abilities, while learners with higher spatial abilities benefit from 3D spatial models. Instead, this study supports the findings of Huang & Lin (Huang & Lin, 2017), which indicate that spatial ability training has a more significant effect on students with weaker spatial abilities. As for why the high-scoring group did not show a significant improvement in pre and post-test scores, the reason may be the ceiling effect, where high-scoring students generally have higher scores, leaving less room for improvement.

(3) The Impact of the Course on Students of Different Genders.

In the pretest, male students scored higher (20.17±7.16) than female students (18.11±7.32), but this difference was not statistically significant (t=1.18, p=0.24>0.05). The reasons for this difference have been discussed in the previous theoretical explanations, mainly due to the co-occurrence of spatial ability tests and gender. The results of paired-sample t-tests showed that female students had a significant improvement in spatial abilities (t=2.87, p=0.01), while male students, although showing some improvement in spatial abilities, did not demonstrate statistical significance (t=0.88, p=0.39). The possible reason is also the ceiling effect. This aspect further illustrates that the "Three-Dimensional Modeling and Printing" course can enhance spatial abilities and, through the course and training, compensate for the gender-related differences in spatial abilities (which are specific to certain spatial abilities).

5.2 DISCUSSION

5.2.1 Improve Chinese Undergraduate Students' Spatial Ability

This study evaluates the spatial ability of Chinese college students who were about to take the "3D Modeling and Printing" course through a demographic survey and a spatial ability test. The spatial ability test adopted the Re-vised PSVT: R, with no time limit and online test method. This paper reports the process of the evaluation, the results of the data analysis, and the subsequent conclusions, and provides suggestions for using the tool as an evaluation tool. The test results show that PSVTR can effectively assess the level of students' spatial ability, and there are significant differences in spatial ability in gender and major, but no other related factors were found. In terms of test score, male is significantly higher than female, and students majoring in STEM are significantly higher than non-STEM; in terms of test speed, male are significantly faster than female, but there was no significant difference in majors. Test scores and time were moderately positively correlated, but there was no significant difference in test time among students with upper-intermediate test scores.

Through the assessment results, the spatial ability level of students can be identified and the situation of students can be understood. In addition to being used as an identification tool, assessment can also be used to inform the development of strategies for such spatial thinking lessons to plan for differentiated instruction. In addition, the assessment results are also the before and after measures of the students' spatial ability changes before and after the course is carried out. For example, in the course development and implementation process, through 3D printing technology, students are provided with more physical course models; rich graphics and image materials are provided; more students are allowed to analyze and construct models in the computer environment; let students do more hands-on operations, such as 3D printing of models.

5.2.2 Emerging Technology Integration Enhances Spatial Ability

Emerging Technology (3D Modeling and 3D Printing) offer unique opportunities for students to develop and enhance their spatial abilities. Three-dimensional modeling and 3D printing involve working in a three-dimensional space, which can significantly improve students' spatial reasoning skills. These technologies are widely used in various industries, such as engineering, architecture, and healthcare. By incorporating them into education, students gain practical skills that are directly applicable in their future careers. Three-dimensional modeling and 3D printing bridge multiple disciplines, encouraging interdisciplinary learning. Students can apply spatial concepts in diverse fields, fostering a holistic understanding of spatial abilities. Working with these technologies challenges students to think critically and solve complex problems. They need to understand how objects and structures interact in three-dimensional space, promoting analytical skills. These technologies allow students to unleash their creativity. They can design and create physical objects, encouraging innovative thinking and design skills.

Therefore, firstly, it is necessary to conduct teacher training to ensure that educators are proficient in these technologies and can effectively teach students. It is also necessary to develop dedicated courses like "Three-Dimensional Modeling and Printing" that focus on spatial skills development. It provides students with access to 3D printers and modeling software, allowing them to learn by doing. Teachers should assign projects that require students to create and print three-dimensional objects, thereby strengthening their spatial thinking. Promoting collaborative learning and encouraging teamwork help develop students' communication and problem-solving abilities. Simultaneously, appropriate assessments, such as spatial ability tests, should be conducted to measure the impact of integrating these technologies on students' spatial abilities.

In summary, integrating three-dimensional modeling and 3D printing technologies into education is vital for enhancing spatial abilities, preparing students for real-world applications, and promoting interdisciplinary learning, problem-solving, creativity, and innovation. Various methods and approaches can be employed to effectively incorporate these technologies into the curriculum.

5.2.3 Limitations and Future Prospects

5.2.3.1 Limitations

During the course of this study, while significant research outcomes were achieved, there were also several limitations, mainly as follows: 1) Due to the convenience of sampling and a small sample size, there may be limitations in generalizing the results of this study to other populations in different educational settings. 2) This study was conducted online, without time constraints, and the grouping variables and demographic information relied on participants' self-reports, potentially introducing response bias that could affect the study's results. 3) Due to limitations in time and resources, the integration of emerging technologies into conventional course instruction needs further refinement, and course resources need to be further enriched to support practical activities aimed at improving spatial abilities within the constraints of limited classroom teaching time. 4) Using the same test items for both pre-test and post-test assessments may introduce a testing practice effect from the pre-test, which could influence the test results.

These factors have had some impact on the study's outcomes, to some extent leading to its limitations that require further improvement. However, overall, this study has taken a foundational step in researching the integration of emerging technologies into education to enhance spatial abilities among university students. The research process, methodology, literature review, and practical experience gained from this study also hold reference value for future research. It has provided a basis for the author's learning in this field and will guide future in-depth research, offering new directions and insights.

5.2.3.2 Future Prospects

Spatial ability is highly important in many fields, including engineering, architecture, medicine, and the arts, among others. Integrating emerging technologies to enhance the spatial ability of university students is both a societal and personal growth necessity. Therefore, integrating emerging technologies and developing and implementing courses related to spatial thinking is a promising educational initiative that can help university students improve their spatial abilities. For future research directions and prospects, the following aspects are primarily considered:

(1) Spatial Ability: Develop more accurate and reliable measurement tools to assess the spatial ability of university students. These tools can incorporate traditional tests and modern technologies such as virtual reality (VR) and augmented reality (AR). Additionally, research different cultural and age groups' performance in spatial ability to enable personalized education and training.

(2) Educational Technology and Virtual Reality: Investigate how to use virtual reality (VR) and augmented reality (AR) technologies to enhance the effectiveness of 3D modeling and printing courses. Explore interactive educational tools based on VR and AR to improve students' spatial cognition and problem-solving abilities.

(3) Interdisciplinary Research: Promote the integration of spatial ability research with other disciplines such as educational psychology, neuroscience, computer science, engineering, and others to deepen our understanding of spatial abilities. Study the relationships between spatial ability and other cognitive skills, such as mathematical ability and logical reasoning. Encourage cross-disciplinary integration of 3D modeling and printing courses with fields like arts, engineering, medicine, and social sciences to broaden students' horizons.

(4) Personalized Learning and Education: Develop personalized learning systems that tailor educational content and methods based on students' spatial ability levels and learning styles. Utilize big data and machine learning techniques (educational data mining) to provide real-time feedback and recommendations, assisting students in improving their spatial abilities.

(5) Educational Assessment and Effects: Conduct long-term studies to evaluate the impact of 3D modeling and printing courses on students' spatial abilities and career development. Compare the effectiveness of different teaching methods and course designs to identify best practices. Simultaneously, research the relationship between spatial ability and various professional fields, including engineering, architecture, medicine, arts, etc., to determine how these abilities can be applied in careers. Foster collaboration with industries to translate research outcomes into practical training and career development opportunities.

In summary, future research will delve into how to fully integrate emerging technologies to enhance the spatial abilities of university students. This will provide more opportunities in the field of education to meet the evolving demands of technology and careers, nurturing a new generation of university graduates with excellent spatial abilities who will make positive contributions to future scientific research and innovation.

APPENDIX A

Jiaying University General Elective Course Construction Standards

Primary Indicator	Secondary Indicator	Main Construction Points
Teaching Content	1-1 Course Objectives	In line with the general education philosophy, this guides students to explore a wide range of knowledge across different subject areas, enhancing their understanding of themselves, society, nature, and their relationships. It aims to nurture a well-rounded personality, a tolerant attitude, a broad perspective, critical thinking, a strong sense of social responsibility, humanistic concern, and a spirit of pursuing truth.
	1-2 Course Content	Basic Nature: It is conducive for students to understand the most fundamental knowledge domains and thinking methods of humanity. Integrative: It integrates and comprehensively recognizes content from different disciplinary areas. Guiding: It contributes to the development of students' complete rationality, healthy personality, positive emotions. Universal: It is generally applicable to students from various majors without the prerequisite of prior systematic specialized knowledge.
Teaching Reform	2-1 Teaching Research	Teaching Ideology: It encourages active teaching thoughts and creative teaching reforms. Participation in Teaching Research: Actively participates in teaching research and drives teaching reform, undertaking teaching reform projects.
	2-2 Teaching Methods	Student-Centered: Emphasizes individualized instruction, stimulates intellectual development, and encourages reading classics, in-depth discussions, critical analysis, and training in multidisciplinary research methods and thinking. Diverse Teaching Methods: Encourages the use of various teaching methods to enhance student engagement. Focus on the Learning Process: Explores scientific assessment methods and approaches.
	2-3 Educational Technology	Modern Educational Technology: Utilizes modern educational technology and online resources to improve learning outcomes. Online and Blended Learning: The course can be conducted as online or blended learning on the school's curriculum center platform.
Teaching Resources	3-1 Basic Resources	Basic Resources: Core resources reflecting the teaching ideology, content, methods, and processes of the course, including teaching videos, course descriptions, syllabi, lesson plans or presentation materials, key and difficult point guidance, assessments, reference material lists, etc.
	3-2 Teaching Materials Development	Quality Teaching Materials: Selection of excellent textbooks or the development of high-quality, suitable teaching materials or internal lecture notes that align with the correct political direction and value orientation.
Teaching Management	4-1 Teaching Schedule	Course Frequency: Offered at least once every semester.
	4-2 Teaching Effectiveness	Popularity: The course is well-received by students, with high enrollment and multiple class sections.
	4-3 Promotional Value	Demonstration and Promotion: The course has a demonstrative and radiating effect with strong measures for course sharing, making it suitable for future promotion in other universities.

APPENDIX B

Ethics Review Form of the Medical Ethics Committee of Jiaying University

嘉应学院医学伦理委员会伦理审查表

NO: JYYXLL2022-03

项目名称	开发《三维建模与3D打印》课程提高大学生空间能力				
承担专业	物理	承担责任	☑负责 □参与	申请人	杨伟志
研究分类*	1☑ 2□		研究起止时间	2022.09-2022.12	
审查目的	□科研项目申报 ☑科研项目实施				
所在单位	物理与电子工程学院				
课题来源	□政府 □基金会 □公司 □国际组织 ☑其他				
递交审查资料：□项目申请书 □研究论文 ☑ 其它					
联系电话：15219712622					
研究主要内容： 本研究主要是通过开发和实施《三维建模与3D打印》课程，提高大学生的空间能力。该课程为全校公选课，研究对象为选择该课程的学生。在课程开始阶段进行一份问卷和测试，在课程结束阶段进行后测。问卷和测试都采用线上测试，在“问卷星”上形成，学生在手机移动端完成，不限时间。测试采用翻译为中文的《修订版普渡空间可视化测试：旋转可视化》（Revised Purdue Spatial Visualization Test: Visualization of Rotations, PSVT:R），是一种测量13岁及以上个体三维心理旋转空间可视化能力的仪器。心理测量仪有2个练习项目,然后是30个测试项目，包括13个对称和17个不对称的三维物体的图形，它们是以二维等距格式绘制的。					
审查结果	**审查意见：** 经审查，该研究的实验设计和方案充分考虑了安全性和公平性原则，充分保护了实验受试者知情同意权。研究内容和研究结果不存在利益冲突。 医学伦理委员会主任委员签章： 日期：2022.9.5 嘉应学院 医学研究伦理委员会				
	伦理委员会意见： ☑同意 □修改后同意 □修改后重审 □不同意 嘉应学院科技伦理委员会公章： 嘉应学院 科技伦理委员会 日期：				
*研究分类：1=涉及人体实验；2=涉及组织或细胞实验					

Ethics Review Form of the Medical Ethics Committee of Jiaying University

NO: JYYXLL2022-03

<table>
<tr><td>Project Name</td><td colspan="5">Develop Three-dimensional Modeling and Printing Course to Improve College Students' Spatial Ability</td></tr>
<tr><td>Undertake Major</td><td>Physics</td><td>Duty</td><td>☑responsible
☐participant</td><td>Proposer</td><td>Weizhi Yang</td></tr>
<tr><td>Research Classification*</td><td colspan="2">1 ☑ 2 ☐</td><td>Researching Time</td><td colspan="2">2022.09-2022.12</td></tr>
<tr><td>Purpose of Review</td><td colspan="5">☐ Research project application ☑ Project implementation</td></tr>
<tr><td>Affiliation</td><td colspan="5">School of Physics and Electronic Engineering, Jiaying University</td></tr>
<tr><td>Subject Source</td><td colspan="5">☐ Government ☐ Foundation ☐ Company ☐ International organization ☑ Other</td></tr>
<tr><td colspan="6">Submission of Information for Review : ☐Project proposal ☐ research paper ☑ Other</td></tr>
<tr><td colspan="6">Contact Number: 15219712622</td></tr>
<tr><td colspan="6">Research content: This study aims to improve the spatial ability of college students through the development and implementation of the course "3D Modeling and 3D Printing". This course is a public elective course for the whole school, and the research object is the students who choose this course. A questionnaire and test will be given at the beginning of the course and a post-test at the end of the course. Both the questionnaire and test are conducted online, which are formed on the "Wen Juan Xin" and completed by students on their mobile phones for unlimited time. The test will be conducted using the Revised Purdue Spatial Visualization Test: Visualization of Rotations (Revised PSVT:R, Chinese Version), which is an instrument that measures the ability of individuals aged 13 years and older to visualize the three-dimensional mental rotation space. The psychometric instrument has 2 practice items followed by 30 test items that consist of 13 symmetrical and 17 asymmetrical figures of 3-D objects, which are drawn in a 2-D isometric format.</td></tr>
<tr><td rowspan="2">Review Result</td><td colspan="5">Review comment:
After review, the experimental design and program of this study fully considered the principles of safety and fairness, and fully protected the right of informed consent of experimental subjects. There is no conflict of interest between research content and research results.

Signature..
(Chairman of the Medical Ethics Committee)
Date: 2022-09-05</td></tr>
<tr><td colspan="5">Ethics Committee opinion:
☑ Consent ☐ Modified consent ☐ Retrial after modification ☐ Disagree

Stamp..
(Science and Technology Ethics Committee, Jiaying University)
Date:</td></tr>
<tr><td colspan="6">* Research classification: 1 = Involving human experimentation; 2= Experiments involving tissues or cells</td></tr>
</table>

APPENDIX C

Revised Purdue Spatial Visualization Tests: Visualization of Rotations

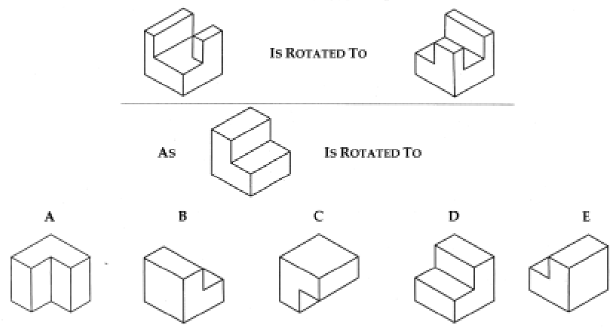
Revised Purdue Spatial Visualization Tests:
Visualization of Rotations
(Revised PSVT:R)

So Yoon Yoon

- DO NOT open this booklet until you are instructed to do so.
- DO NOT make any marks in this booklet.
- MARK your answers on the separate answer sheet.

DIRECTIONS

This test consists of 30 questions designed to see how well you can visualize the rotation of three-dimensional objects. Shown below is an example of the type of question included in the second section.



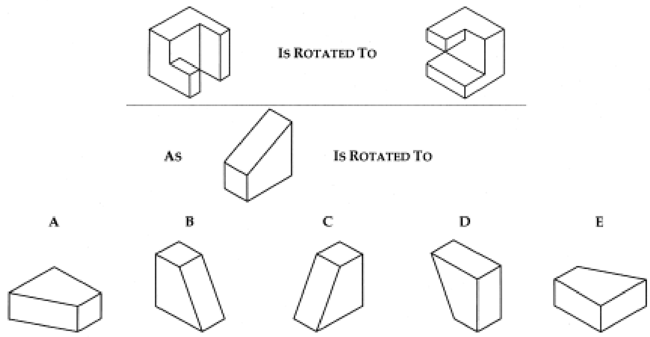
You are to:

1. study how the object in the top line of the question is rotated;
2. picture in your mind what the object shown in the middle line or the question looks like when rotated in exactly the same manner;
3. select from among the five drawings (A, B, C, D, or E) given in the bottom line of the question the one that looks like the object rotated in the correct position.

What is the correct answer to the example shown above?

Answers A, B, C, and E are wrong. Only drawing D looks like the object rotated according to the given rotation. Remember that each question has only one correct answer.

Now look at the next example shown below and try to select the drawing that looks like the object in the correct position when the given rotation is applied.



Notice that the given rotation in this example is more complex. The correct answer for this example is B.

APPENDIX D

Mahasarakham University Ethics Committee

For Research Involving Human Subjects

MAHASARAKHAM UNIVERSITY ETHICS COMMITTEE FOR RESEARCH INVOLVING HUMAN SUBJECTS

Certificate of Approval

Approval number: 364-411/2023

Title : Development of Three-dimensional Modeling and Printing Course to Improve College Students' Spatial Ability.

Principal Investigator : Weizhi Yang
Responsible Department : Faculty of Education
Research site : Guangdong Jiaying University, China

Review Method : Expedited Review

Date of Manufacture : 25 September 2023 **expire :** 24 September 2024

This research application has been reviewed and approved by the Ethics Committee for Research Involving Human Subjects, Mahasarakham University, Thailand. Approval is dependent on local ethical approval having been received. Any subsequent changes to the consent form must be re-submitted to the Committee.

Ratree S.

(Asst. Prof. Ratree Sawangjit)
Chairman

Approval is granted subject to the following conditions: (see back of this Certificate)

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