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ENHANCING STEM/STEAM EDUCATION THROUGH SPATIAL THINKING AND DIGITAL TOOLS

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Abstract

Spatial thinking has a long history in cognitive psychological studies. As one of the most heavily researched segments of the human psyche, it pertains to the ability to generate, retain, retrieve, and transform visual images. Stemming from over a century of research, spatial thinking is a fundamental cognitive process that plays a crucial role in many disciplines.

This project will discuss the significance of spatial thinking in the context of STEM/STEAM education and seeks to emphasize the role of spatial and digital tools in enhancing learning outcomes. As STEM/STEAM educators leverage visualizations and representations to communicate complex concepts, spatial and digital learning tools emerge as comprehensive and practical aids. Beyond traditional graphics, tables, and maps, these tools encompass 3D models, projections, photographs, graphs, diagrams, and sketches. The project argues that spatial thinking, a concept that is teachable and already integrated into education, can be further improved through technology, leading to positive educational outcomes derived from various forms of thinking and highlighting the unique nature of spatial thinking while engaging multiple thinking styles simultaneously. The importance of spatial thinking is further emphasized by its application in STEM and design programs and in arts and literature-based programs.

Introduction

Spatial thinking represents the human ability to generate, retain, retrieve, and transform visual images (Lohman, 1993). Spatial thinking has a long history in cognitive psychology studies (Uttal, 2012). Studies on spatial thinking date back more than 100 years. Psychological research has been focused on identifying humanity's spatial thinking and reasoning abilities and has subsequently made spatial thinking and reasoning one of the most researched human cognitive processes (Uttal, 2012; Carroll, 1993; Mohammadi-Aragh et al., 2022). As STEM/STEAM educators, we use visualizations and representations, such as graphical and sensory observations, to better communicate objects' structure, operation, and function and their respective relationships (Harris, 2021). Spatial and digital learning tools are more comprehensive than graphics, tables, and maps. There are 3D models and projections, photographs of objects, graphs, diagrams, and even simple sketches and drawings indicating spatial data relationships.

Available spatial tools support spatial thinking and are as critical in learning and development as verbal and mathematical thinking are for success in STEM/STEAM programs. Because spatial thinking can be taught and is something we do in schools already, spatial tools can be associated with improving educational outcomes. Faculty use available tools and technology to aid in developing a student's spatial thinking and require further employment and application to continue making progress. There are already some excellent techniques for developing spatial thinking through practice, language, gestures, maps, diagrams, sketching, and analogy. Systematically expanding these techniques into the curriculum via technology will yield essential and positive educational outcomes (Newcombe, 2010).

Types of thinking

There are many forms of thinking. Some include verbal, symbolic, hypothetical, logical, mathematical, and statistical. These forms of thinking are often distinguished by their respective representative or reasoning systems, whether verbal or mathematical, rational or metaphorical (Nutt, 1922; Taba, 1965). Learners may use multiple forms of thinking in any combination in any learning environment. Topics such as science may require linguistic, hypothetical, mathematical, logical, and many other thinking processes. Spatial thinking or Spatial-Computational Thinking is unique because it utilizes multiple thinking styles simultaneously (Newcombe et al., 2015; Wing, 2006).

Definitions and Uses of Spatial Thinking

Spatial thinking is "the knowledge and skills to use concepts of space, tools of representation like maps and graphs, and reasoning processes used to organize and solve problems" (Downs et al., 2005). As STEM/STEAM educators, we can use visualizations and representations in a variety of different media, such as graphics (video, text, and images), as well as sensory observations, such as tactile, auditory, and kinesthetic, to better communicate the structure, operation, and function of objects and their respective relationships to one another (Harris, 2021). Powerful spatial learning tools include graphics, tables, and maps. There are 3D models and projections, photographs of objects as seen through microscopes and telescopes, graphs and diagrams, sketches and drawings as a matter of record of observations, or as people work to communicate scientific findings. From an early age, students are taught through two-dimensional (2D) representations, in books or on blackboards (as a cost-saving measure), or because that was the standard of education at the time or because that was what the district had access to. The world around us is three-dimensional (3D), and the students are better served by being taught from a spatial (3D) perspective. Using digital technologies and implementing a spatial thinking mindset in the classroom sets the standard for better student understanding of the 3D world in which they live. Spatial thinking allows students to solve more complex location-oriented problems, investigate and further understand their data from a geographic perspective, determine connections and relationships, detect and quantify patterns, evaluate trends, and make effective decisions based on those analyses. Research shows that students with greater spatial ability have a better learning outcome when using visualizations and spatial learning than those with a lower spatial ability (Hoffler, 2010). With these differences in learning style and ability, a greater spatial ability will predict greater interest levels and potential further success in STEM fields. It will also account for higher verbal and mathematical abilities. It also stands to reason that high school students with higher-than-average spatial learning scores are likelier to work in STEM fields after graduation (Wai et al., 2009; Sun et al., 2022; 2023).).

Based on this evidence, spatial thinking should not be restricted to any particular knowledge or educational domain. While it may be more characteristically applied in the STEM and design programs, it can also be successfully used to support arts and literature-based programs, including the use of sketching software to facilitate learning spatial concepts (Forbus et al., 2011) or computer spatial visualizations to conduct virtual scientific experiments or express design concepts (Linn et al., 2011). Scientists often make sketches as observations or ideas develop during collaborations, with obvious spatial thinking benefits. In contrast, typical classroom students are frequently asked to interpret existing visualizations (those created by others) rather than being asked to make their sketches. Significant research has revealed that active sketching (showing spatial and visual acuity) enhances understanding and conceptual engagement in multiple dimensions while further deepening students' understanding. Student sketches require thought and reasoning, force ideas and concepts to be made explicit, and further support communication among learning groups (Newcombe, 2013). This approach requires students to learn and apply information to science and engineering principles. Spatial thinking is a way of thinking. It has distinctly different applications in different disciplines. It requires a knowledge or understanding of physical space, distance, dimensions, relationships, and representations and the ability to use and apply reasoning to make judgments and understand spatial concepts.

Importance of Spatial Thinking in STEM Fields

STEM fields depend significantly on both spatial thinking and spatial and digital tools. Most STEM programs involve thinking about the transformation of physical or spatial structures across time and space, and these processes are often, if not always, spatial. Some researchers and educators have developed (or refined) spatial training procedures designed to enhance spatial thinking and use spatial or digital tools to help prevent dropouts from STEM fields. Spatial skills are also very flexible and applicable everywhere. Therefore, the effects of spatial thinking and its subsequent training can be conveyed to many other educational systems and programs beyond STEM (Uttal & Cohen, 2012; Harris et al., 2021). Most research linking spatial abilities and STEM education has focused on what Carroll (1993) described as "*spatial visualization*," or the process of apprehending, encoding, and mentally manipulating three-dimensional spatial systems. Some spatial visualization tasks involve relating two-dimensional and three-dimensional representations and vice versa. Spatial visualization is a sub-factor relevant to thinking in many science disciplines, including geology, biology, chemistry, and physics). Discipline-based perspectives of spatial thinking from the National Research Council report and the disciplined-focused views used by Atit et al. (2020) in their review of research on spatial thinking skills used by experts in the fields of geology and medicine indicate that spatial thinking in STEM disciplines include solving spatial problems which require use of domain knowledge, and spatial thinking (context-dependent and domain knowledge-integrated), as well as identification of spatial problems occurring in STEM contexts (Mohammadi-Aragh et al., 2022). Many other studies have shown moderate-to-strong correlations between various measures of spatial skills and performance in particular STEM disciplines. As applied to specific STEM fields, spatial visualization tasks involve imagining the shape and structure of two-dimensional sections, or cross sections, of three-dimensional objects or structures. Mental rotation is sometimes considered a form of spatial visualization, although other researchers consider it a separate factor or skill (Linn et al., 1985). Spatial thinking plays a significant role in STEM fields. These fields require external spatial representations (e.g., graphs, computer visualizations with spatial aspects) and even simple STEM reasoning (Gunderson et al., 2012), for example, using the number line in elementary mathematics. One of the most recent trends in STEM education is the use of computer programming in K-12 classrooms to develop and enhance what researchers have come to call spatial-computational thinking in students, a skill defined by Wing (2006) and

Scherere (2016) as one that "*involves problem solving and system design, as well as developing an understanding of human behavior, through the use of concepts typicially considered limited to computer science*." The National Research Council (2005, 2006) published the report Learning to Think Spatially, highlighting spatial thinking as the thought process that "*is integral to everyday work of engineers and scientists*" and "*has underpinned many scientific and technical breakthroughs.*" Although Spatial-Computational Thinking is not limited solely to computer science (Denning, 2009), research shows that programming is an excellent method to develop this competency (Lewis et al., 2012).

As we move further into the 21st Century, and as schools begin to lean away from traditional educational methods and more toward experiential learning and spatial-computational thinking and associated concepts, teachers would be wise to take advantage of student's excitement about technology, gaming, and robotics to broaden students' participation in the STEM classroom and also to engage students in an integrated curriculum (Barr et al., 2011). Schools leading this pedagogical change redesign the curriculum to include robotics and game design during the school day and use spatial-computational thinking concepts to underpin the lessons. (Repenning et al. 2010). This fundamental pedagogical shift creates technology-rich teaching and learning environments with long-lasting educational implications as we move into the future (Li, 2010). Spatial-computational thinking and its role across STEM disciplines are being acclaimed for their role in the contemporary learning environment. They have also been identified as pathways to broaden participation in STEM and STEM-related careers (Sheridan et al., 2013). Over the past decade, researchers in psychology, education, and other disciplines have increasingly investigated the role of spatial thinking in STEM field achievement (Uttal and others, 2013). For our purposes, spatial thinking can be defined as a collection of cognitive skills consisting of both indicative and perceptual forms of knowledge and using mental skills to transform, combine, or otherwise apply this knowledge in solutions and problem-solving. Spatial thinking (or spatial reasoning as some call it) refers to the "*ability to generate, retain, retrieve, and alter visual images so they can be better understood and utilized by the learner*" (Lohman, 1994). This includes "*the rotation, retention, and transformation of information in a spatial context*." Spatial thinking skills can be learned or expanded to improve student learning outcomes (Ramful et al., 2017). The National Academy of Sciences, the National Research Council (2005, 2006), and Fiantika (2017) have further defined spatial thinking and reasoning as a collection of cognitive skills. Spatial thinking skills consist of declarative and perceptual forms of knowledge and using cognitive operations to transform, combine, or otherwise use knowledge. Spatial ability was described as intelligence distinct from verbal ability almost 140 years ago (Galton, 1883). The measurement of spatial ability was predominantly conducted with methods developed by psychologists (Hegarty & Waller, 2005). The key to spatial thinking combines three primary components: concepts of space, how the idea is represented, and reasoning processes (Harris, 2021). In the future, Spatial thinking or Spatial-Computational Thinking will be fundamental to human adaptation and contemporary living.

Spatial Thinking Terminology

To understand the construct of spatial thinking, you need the basics of spatial thinking vocabulary. Spatial terminology varies across disciplines, country of origin, and research intent. One reason may be that the richness of our mental imagery could be better articulated by our linguistic capabilities (Hayward et al., 1995). Subsequently, various terms have been used to define spatial concepts with little consistency. Essential spatial vocabulary provides a shared conceptual framework that needs improvement within the literature. The term ability is often used to differentiate students in education and has been defined as a "*salient psychological attribute*" (Wai et al., 2009), implying it is stable over time. By contrast, spatial skills suggest growth and change opportunities (Uttal et al., 2013). More generally, spatial reasoning invokes thoughts of non-verbal problem-solving, while spatial thinking conjures up images of a habit of mind or more holistic spatial sense (Whiteley et al., 2015). These terms are distinct from the mental processes that occur during spatial tasks. Visual imagery (imagining a referent object(s) Presmeg, 1986) and spatial relations (relative position or movement between objects; Hegarty & Kozhevnikov, 1999)

Spatial Skills

Spatial skills are the measurable components of spatial reasoning that are distinct but related to one another (Carroll, 1993). Newcombe and Shipley (2015) proposed a classification of spatial tasks defined by the characteristics of the studied object or concept(s), whether they remained static or were in motion, and whether spatial relations were fundamental or extraneous. This framework provides students with the foundations for linking the thought processes undertaken during spatial tasks and skills in other fields, such as mathematics. However, the classification proposed by Newcombe and Shipley is primarily based on psychological tests and has yet to be supported by further research or in applications beyond lab-based studies (Mix et al., 2018). The idea of assessing different spatial skills initially emerged in aptitude testing for occupations (Hegarty et al., 2005). As these psychometric tests continued to evolve, correlations with other skills and outcomes emerged. For example, spatial skills were the strongest predictor of success in STEM fields and career choice across a 50-year longitudinal study (Wai et al., 2009), ranking above verbal ability and mathematics proficiency.

The concept of space, therefore, makes spatial thinking a distinctive form of thinking. By understanding the idea of space, we can use its properties to understand problems better and develop valuable solutions or answers to those problems. By expressing relationships within spatial structures such as 2D maps, 3D models, or other computer-aided visualization systems (like Integrated Data Viewer), students will better distinguish, recall, and be able to evaluate the properties and relationships between objects or problems.

Conclusions

Improving spatial thinking provides the skills necessary to succeed in STEM fields. A specific focus on spatial thinking is lacking in almost all educational programs. Additional research is needed to specify which training methods will lead to significant STEM-related improvements. Like any cognitive skill, spatial thinking can improve if developed. Gaps in recent literature remain, and systematic studies of spatial skill interventions have yet to be conducted to determine their contribution to learning outcomes. Research studies remain either isolated (Cheng & Mix, 2014: 3D mental rotation; Lowrie et al., 2019: spatial visualization) or merged (Lowrie et al., 2017), making it challenging to identify the unique contributions of spatial skill development.

To effectively further the concept, spatial thinking must be integrated into real-world applications (Lowrie et al., 2020). Programs like the 3D visualization teacher summer workshops conducted as part of the Mississippisd State University – NSF Collaboration, could be expanded to more participants and rolled into the classroom for student use (Sun et al., 2021; 2023). Spatial instruction must be explicit and targeted to specific disciplines, not merely fostered by including more spatial content within the curriculum. There needs to be shared meaning to bridge the gap between cognitive theories of spatial thinking relations and classroom practical application of spatial thinking, and further studies need to be conducted at scale with teachers included and instrumental in the process. Finally, experimental design must allow for decisions about the tools that connect spatial thinking, reasoning, and skills with a better understanding of the curriculum to ensure a positive and sustainable outcome for students and faculty.

Spatial and digital tools are crucial to improving STEM teaching and learning and developing spatial thinking. The apparent need to enhance STEM programs in 21st-century education has led to a shift in teaching and learning. The quality of learning outcomes is directly impacted by integrating spatial and digital tools and access to technology and information in general. (Chen et al., 2010; Claro et al., 2012). Technology is helping to strengthen student learning processes and outcomes (Mishra, 2019). Integrating these tools also helps build effective and collaborative relationships within both students and school communities while continuing to improve learning practices on an ongoing basis (Clark, 2010; Harris et al., 2009; Laurillard, 2009). The success of technological integration in education is directly related to teachers' competence in technology and the design of effective learning material. Applying learning models in the classroom is the primary key to achieving these learning objectives (Sun et al., 2018). Technology and, by proxy, spatial and digital tools have further provided for and enhanced the effectiveness and efficiency of learning to improve knowledge and performance (Laurillard, 2007) by deploying those spatial tools and spatial thinking concepts in STEM fields.

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