Spatial Thinking Skills and STEM Connections: How Does this Issue Address Them?

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Abstract

In this editorial, the Editor considered the importance of spatial thinking skills to STEM careers, provided examples of ways scientists use spatial thinking, noted sex and socioeconomic differences in spatial skill proficiency, and reviewed ways that activities included in articles in this issue involved spatial thinking. Brief summaries and preview images were provided for the articles in the issue. The four-component spatial thinking classification scheme with categories of intrinsic-static, intrinsic-dynamic, extrinsic-static and extrinsic dynamic was applied to the activities from this issue of the *Journal of STEM Arts, Crafts, and Constructions.* All categories of this classification scheme were addressed, providing examples for practitioners and parents to consider implementing with youth.

Key Words

Spatial thinking skills, Arts-integration, STEM education, STEAM education

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Spatial Thinking

Functioning in our three-dimensional world requires spatial thinking about shapes, locations, and paths of objects along with relationships among objects and frames of reference (Newcombe & Shipley, 2015). Individuals use spatial thinking skills in their everyday lives as they differentiate unripe, ripe, and over-ripe fruit in a supermarket; choose furnishing styles, sizes, and colors that will complement their current home décor; drive to a new address; or examine election results on a map. Spatial thinking encompasses "the mental processes of representing, analyzing, and drawing inferences from spatial relations" (Uttal, Miller, & Newcombe, 2013, p. 367).

Recognition of the differences between the *intrinsic* spatial properties of objects, such as their shapes and configurations of parts (consider the similarities and differences between a fork and a spoon) and *extrinsic* relationships such as connections between objects and frames of reference (e.g., "Turn right at the tall building, then go three blocks before turning left") can be useful in spatial thinking (Chatterjee, 2008). Another important consideration is the distinction between static (stationary objects) and dynamic (objects in-motion) spatial thinking skills. A four-category classification scheme has been developed that encompasses these factors: 1) Intrinsic-static; 2) Intrinsic-dynamic; 3) Extrinsic-static; and 4) Extrinsic-dynamic (Newcombe & Shipley, 2015). These categories will be explored in more detail in a moment.

Let us first turn to spatial thinking in science. The work of scientists often requires recognition of patterns or shapes of objects and relationships between objects in space. Consider a surgeon planning an operation, an orthodontist aligning teeth into a smooth arc; a geologist determining the hidden underground shape of a rock formation; a chemical crystallographer studying the structure of a new compound; an astronomer determining a near-earth asteroid's path; or a biologist studying plankton. All of these scientists are making use of visual-spatial thinking as they use their eyes to locate, identify, and perceive spaces and configurations of objects and the relationships between them. To analyze these relationships, they form, inspect, transform, and maintain images in the mind's eye or use photographs, diagrams, graphs or other visuals (Mathewson, 1999). Now, let's expand on some of these scientific activities and apply the four-category spatial thinking classification scheme to determine what types of spatial thinking skills occur. See Table 1 for scientist actions that match the different categories of spatial thinking outlined previously.

Table 1. *Example Scientific Thinking Activities Classified by Spatial Thinking Type with Categories of Newcombe and Shipley (2015)*

Spatial Thinking Category	Typical Operations	Scientific Field	Scientific Activities Involving Spatial Thinking
Intrinsic-static	Identifying spatial features of objects such as color, texture, size and arrangement of parts.	Geology	Identifying rocks and rock formations by color, texture, grain size, and visual patterns
		Chemistry	Determining the arrangement of atoms in the structure of a new substance
		Dentistry	Identifying types of teeth by shape
		Astronomy	Identifying a known asteroid by silhouette
		Biology	Identifying foraminifera by configuration and ornamentation of their shells (tests)
Intrinsic-dynamic	Transforming the spatial relationships of objects such as rotating, cross-sectioning, folding, and plastically deforming.	Geology	Sketching a cross-section of the rocks to show their folding pattern
		Chemistry	Checking the symmetry of atoms in a crystal structure by imagining them moving across mirror planes or rotating about an axis.
		Biology	Differentiating left-coiled from right-coiled tests.
		Dentistry	Folding an x-ray of the mouth to compare tooth positions on each side of the midline
Extrinsic-static	Determining the spatial locations of objects relative to others or to a frame of reference such as the horizontal.	Geology	Measuring strike and dip of rock formations to determine the overall shape and attitude of hidden parts of the formation.
		Dentistry	Identifying missing, partially erupted, and misaligned teeth compared to a model
		Biology	Plotting locations of different specimens on a map
		Chemistry	Comparing the crystal structures of a compound with and without a substituted element
Extrinsic-dynamic	Transforming the inter-relationships of objects as movement occurs among the objects, frame of reference, or the viewer.	Medicine	Determining the best place for an incision and the path to be used for surgery as tissue layers are opened and pieces removed
		Dentistry	Determining the sequence of events, angles and amounts of movement at different times needed to bring teeth into alignment
		Biology	Creating a sequence of maps showing locations of foraminifera as seas warm during global climate change
		Astronomy	Locating a near-earth asteroid's path through time and its distances from Earth as both move along different paths
		Geology	Rotating a map to match one's current location, as one walks across a field area, using the positions of landmarks on the ground.

The Importance of Spatial Thinking Skills to Choosing STEM Careers

Obviously, spatial thinking skills are present in many scientific activities. Self-assessed intrinsic skill scores of experts from different fields on the Philadelphia Spatial Ability Scale (Wai et al., 2009) indicated that professionals in the geosciences, engineering, physical sciences, and geography had the highest scores with biological sciences, computer science, psychology, social sciences, and humanities far behind.

The connection between STEM careers and spatial thinking skills is complex. Strong spatial thinking skills predict achievement in STEM areas (Shea, Lubinski, & Benbow, 2001; Wai, Lubinski, & Benbow, 2009). Researchers (Wai, Lubinski, & Benbow, 2009) conducting a longitudinal study starting with a large nation-wide sample of more than 400,000 high school students, found that higher spatial skill levels predicted later choice of a STEM career, even when mathematics and verbal skills were controlled.

This correlation between spatial thinking and STEM career choice can be attributed to two main factors: 1) the use of spatial thinking and spatial representations such as graphs, maps, and diagrams in STEM disciplines; and 2) challenging gateway courses into STEM fields that form barriers because students generally have not acquired sufficient content knowledge *unless* students use spatial abilities to solve the difficulties (Uttal & Cohen, 2012). Overall, the performance of experts in STEM areas is not highly correlated with spatial ability because STEM experts have deep content knowledge that allows them to navigate their work; however, students just entering the field of study need to have strong spatial skills to succeed in passing gateway classes (Uttal & Cohen, 2012). Therefore, spatial thinking skills are very important in primary and secondary schooling. Not only is there the problem of spatial thinking skills being rarely taught in k-12 schools, but a gender gap exists that needs attention.

Spatial thinking skills form one of the most persistent gender achievement gaps with males outperforming females by a medium to large margin, especially in skill (Voyer, Voyer, & Bryden, 1995). The good news is that individuals can improve their spatial-visualization skills fairly quickly with training and practice to close the achievement gap (Sorby, 2009; Sorby & Baartmans, 2000).

Sex differences in spatial thinking performance appear in early childhood; a study comparing preschoolers' performance on mazes in the WPPSI-R and mental rotation or translation of objects found differences emerged at approximately age four and a half years (Levine, Huttenlocher, Taylor, & Langrock, 1999). Children in these studies performed the same on vocabulary tests, indicating that the differences were in spatial skills, rather than general intelligence.

Socio-economic status differences in children's spatial thinking abilities have been found (Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005). In this study of second and third graders, only boys of middle and high socioeconomic backgrounds outperformed their female counterparts on mental rotation and spatial syntax comprehension tasks. Children of both sexes classed as low socioeconomic status performed the same. This finding indicates that ability differences are not present in the population as a whole, but are environmental in origin (Levine et al., 2005). These authors suggested that the high level of engagement of middle and high socioeconomic status males in play activities that practice high levels of spatial thinking are the foundation of the male advantage.

Because spatial skills are not innate, but developed, young people should be encouraged to play with construction toys, puzzles, or toys that can be taken apart and put back together, to draw and sketch, and to work with their hands (Hill, Corbett, & St Rose, 2010). School activities that involve students in constructing items from various materials, in producing papercrafts, in creating maps and diagrams, and in making models support spatial thinking skills.

Connections to Spatial Thinking of Articles in this Issue

When arts or constructions are incorporated into STEM areas, spatial thinking skills become a part of the activities. In this section, each article of this issue of the

Journal of STEM Arts, Crafts, and Constructions is highlighted to provide a preview of the issue's content, but also to analyze the types of spatial thinking skills involved in the activities described in those articles.

Guest Editorial

In a guest editorial titled, **Using creativity from art and engineering to engage students in science**, Mason Kuhn, Scott Greenhalgh, and Mark McDermott (2016) discuss the role of the arts in STEM learning. Creative processes of the arts can be a way to gain access to students' ideas before science content is taught, thereby providing guidance of appropriate lesson design to enhance existing student knowledge. The creative aspects of the arts can also be a means for students to express their understanding of science content. In the paragraphs below, a few examples of how the arts employ spatial thinking skills are provided.

Intrinsic-static spatial skills. The arts can involve spatial thinking through drawing, painting, and modeling. These visual arts activities require the artist to make careful observations of the subject, transferring those ideas to the medium. Many of these endeavors involve intrinsic-static spatial thinking skills such as identification of spatial features of objects like color, texture, size, and arrangement of parts.

Intrinsic-dynamic spatial skills. Creation of papercraft products such as pop-ups, origami, folded and cut designs such as snowflakes or clay crafts of building layers and slicing through them engage students in intrinsic-dynamic spatial thinking skills in which students transform the spatial relationships of objects through folding, rotation, cross-sectioning, and plastic deformation.

Extrinsic-static spatial skills. Mural-painting, sculpture, and diorama-making require students to determine the spatial locations of objects relative to others or to a frame of reference.

Extrinsic-dynamic spatial skills. Mobile-making entails consideration of balance in weight and visual arrangement as objects move. Dance and dramatization exercise changing positions of performers on a stage. These art forms involve transformation of the inter-relationships of objects as movement occurs among the objects, frame of reference, or the viewer.

Practical Articles

This issue presents three practical articles. In the descriptions below, spatial thinking skills that are part of the lessons are examined.

Water play. This article by Jane Cline and Brandy Smith (2016) describes intriguing activities with a vertical water table made by the first author and shown in Figure 1. The project involved preschool children in a literacy- and art-integrated project in which they arranged cups of water with holes drilled near the bottoms of cups to form a stream of flow from top cup to bottom cup. This stream represented the stream in the story *Three billy goats gruff* (e.g., Galdon, 1973, Asbjørnsen & Moe, 1957). Children made watercolor illustrations of characters and bridges for the story as they retold the events. The problem of arranging the cups to allow water to flow from one to another involved extrinsic-dynamic spatial thinking skills.

Figure 1. Preschoolers solving the spatial puzzle of directing a falling stream of water.

Who moved those rainclouds to town? Making windbirds to learn about the power of wind. This practical article by Deepanee Samarakoon and Latisha Smith (2016) involved kindergarten children in the spatial movement of a windsock in the wind. Children constructed the birdlike windsocks themselves from colorful materials, folding and cutting the tissue paper kite tails. They then tested them outside in the wind by attaching them to a tree on the school grounds. Children also generated their own wind by running with the windsocks through the air. These latter explorations involved dynamic spatial thinking skills. See Figure 2.

Figure 2. Two kindergarten children with their windbirds.

Second graders beautify for butterflies. The primary students in this article written by Andrea Anderson and Jessica Meier (2016) created a nature space with plants to attract butterflies and other pollinators at their school to beautify the school grounds and to study the relationships between plants and animals. Students planned environmental messages and facts about pollinators for the concrete pavers by first gathering information and then making sketches. The sketches were implemented on gesso-coated concrete paving stones with permanent markers. See Figure 3 for example paving stones placed in the garden. Students practiced intrinsic-static skills as they made the sketches, but each sketch became a frame of reference for the final work on the concrete paver, exercising extrinsic-static spatial thinking skills.

Figure 3. Example decorated paving stones in the garden.

Research Articles

Three research articles are included in this issue of the *Journal*. These are described in this section with their connections to spatial thinking.

Fourth graders make inventions using SCAMPER and animal adaptation ideas. This research article by Mahjabeen Hussain and Anastasia Carignan (2016) explores techniques of stimulating student invention ideas with a given set of craft and recycled materials. See Figure 4.

Figure 4. Example student inventions

The name of the SCAMPER technique is an acronym for Substitute, Combine, Adapt, Modify, Put to another use, Eliminate, and Rearrange (Eberle, 1972). Students used this technique alone or in combination with animal adaptation ideas that referred to form and function of animal body parts. The authors found that the addition of animal form and function significantly increased creativity.

Spatial thinking skills used in this invention activity were intrinsic-dynamic skills. Students were given a small set of items to transform by rearranging, cutting, folding, and attaching to make their inventions. The inventions on the left side of Figure 4, 4a and 4c, were made under the control condition, while those on the right side of the diagram, 4b and 4d, were made under the experimental condition.

Three- and four-year-olds learn about gears through arts incorporation. This research article by Dessy Stoycheva and Leann Perkins (2016) investigated whether integrating the arts with lessons on gear motion might increase memory for key concepts and improve motivation. Although children remembered concepts about gear motion to a similar degree under both conditions, the arts-integrated condition was found to create a more enjoyable working environment. See Figure 5.

Figure 5. Children exploring motion using gears with attached artwork

Art-integration through making dioramas of women mathematicians' lives enhances creativity and motivation. This research article, authored by Audrey Rule, Dana Atwood-Blaine, Clayton Edwards, and Mindy Gordon (2016), involved fifth grade girls in exploration of the lives of contemporary diverse women mathematicians through creation of a diorama that showed scenes from one of the mathematicians' life and work. Students also wrote an essay of their connections to the featured women with an accompanying pop-up scene on the back of the diorama. The spatial thinking project of making a diorama with a cereal box cut to open like a book with a building attached to the front and a pop-up scene on an extra fold-down flap employed intrinsic-dynamic spatial thinking skills. See Figure 6.

Figure 6. Example dioramas made by students. Note the pop-up construction shown in the middle image that appeared on the back side of the box.

Conclusion

Table 2 provides a summary of the types of spatial thinking used by participants in the activities presented in the practical and research articles of this issue. All of the four main areas of spatial thinking were addressed by articles in this issue. Because spatial thinking skills are crucial to students feeling confident, being successful in the foundational courses for a STEM career, and eventually choosing to enter a STEM career, activities that promote all kinds of spatial thinking in the elementary yeas are important. The authors and *Journal* staff hope these examples inspire practitioners and parents to incorporate more spatial thinking into school and leisure activities.

Table 2. *Example Spatial Thinking Activities in this Issue's Practical and Research Articles Classified by Spatial Thinking Category*

Spatial Thinking Category	Typical Operations	Article	Activity Involving Spatial Thinking
Intrinsic-static	Identifying spatial features of objects such as color, texture, size and arrangement of parts.	Water play by Cline and Smith (2013)	Preschoolers drew pictures of the three Billy Goats Gruff, the troll and bridge, then painted them with watercolors.
		Second Graders beautify for butterflies by Anderson and Meier (2016)	Sketching diagrams of pollinators or identified plants from the garden.
		Art-integration through making dioramas of women mathematicians' lives enhances creativity and motivation by Rule, Atwood-Blaine, Edwards, and Gordon (2016)	Fifth graders paint their papier-mâché dioramas with acrylic paints to form a gradient of two colors.
Intrinsic-dynamic	Transforming the spatial relationships of objects such as rotating, cross-sectioning, folding, and plastically deforming.	Who moved those rain clouds to town? Making windbirds to learn about the power of wind by Samarakoon and Smith (2016)	Kindergarten students fold the tissue paper for the windsock's kite-tail and cutting it to make crinkled narrow strips. Kindergarten students observe the windbird windsock's motion in the wind or in the air as the kindergarten student runs with it.
		Fourth graders make inventions using SCAMPER and animal adaptation ideas by Hussain and Carignan (2016)	When provided a bag of recycled or craft materials, fourth graders made an invention to fit a given theme. They cut or folded the items and attached them with tape or glue, thereby transforming their spatial relationships to create their inventions.
		Art-integration through making dioramas of women mathematicians' lives enhances creativity and motivation by Rule, Atwood-Blaine, Edwards, and Gordon (2016)	Fifth graders fold an icosahedron net to make a three-dimensional icosahedron. Fifth grade students create a pop-up scenes on the back of the diorama that shows images of themselves with the diverse women mathematicians studied.
Extrinsic-static	Determining the spatial locations of objects relative to others or to a frame of reference such as the horizontal.	Second Graders beautify for butterflies by Anderson and Meier (2016)	Using a sketch as a model for making a drawing on a gesso-coated cement paving block with colored permanent markers.
Extrinsic-dynamic	Transforming the inter-relationships of objects as movement occurs among the objects, frame of reference, or the viewer.	Water play by Cline and Smith (2013)	Preschoolers directed the motion of water flowing from a hole in a cup to lower cups by in succession by moving the cups on a vertical pegboard water table and adding more water at the top.
		Three- and four-year-olds learn about gears through arts incorporation by Stoycheva and Perkins (2016)	Preschool children make observations of different-sized plastic toy gears with attached artwork figures to determine the relative motions of the gears and their relative speeds.

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