Spatial Thinking Across the College Curriculum

MICHAEL STIEFF
Assistant Professor, Chemistry/Learning Sciences
University of Illinois, Chicago
Email: mstieff@uic.edu

Spatial thinking is a fundamental component of learning and problem solving in the college curriculum, specifically in the STEM disciplines. From their first courses in physics, mathematics, chemistry, and geology, students are tasked with developing mental models that include information about spatial relationships among components in a physical system. For example, students must learn to recognize important structural features in molecular compounds and geological formations in freshman courses. As students progress through STEM courses, they must learn to reason about increasingly complex spatial systems and how spatial relationships change dynamically over time. For example, physics students must learn to calculate changes in force and momentum based on the spatial trajectory of colliding objects and biology students must learn to identify how electrostatic interactions between amino acids cause proteins to fold into highly ordered structures. It is clear that the study of spatial information and dynamic spatial relations are central to all STEM disciplines.

As a professor of chemistry, I can speak firsthand about the role of spatial thinking at all levels of instruction in the chemistry. A typical, ACS-approved baccalaureate degree in chemistry requires students to complete courses in General Chemistry, Organic Chemistry, Inorganic Chemistry, Analytical Chemistry, Biochemistry, and Physical Chemistry. In each of these courses, students must learn to recognize important spatial relationships within and between compounds. While early instruction involves the identification of common molecular shapes and geometries, more advanced instruction requires students to predict the movement of electrons and atoms as they rearrange in complex multi-step reactions to produce new compounds with distinct structural features. Ultimately, students face significant difficulties in the final courses of the major as they are tasked with identifying symmetry elements (e.g., mirror planes, rotational axes, etc.) in complex molecules and analyzing spectroscopic data to predict the three-dimensional structure of unknown compounds synthesized in the laboratory. Arguably, chemistry is the “most spatial” of all the STEM disciplines.

It is important to note that in chemistry as in all STEM disciplines, spatial thinking involves multiple cognitive processes and mental representations. Perhaps most well known among these is imagistic reasoning or “visualization,” a cognitive process by which students are believed to generate and inspect internal representations that include visual images of spatial information. However, spatial thinking involves the generation and manipulation of internal representations other than analog mental images; spatial thinking also involves reasoning via motor schema and abstract spatial representations. Moreover, spatial thinking does not exclusively rely on internal mental representations, but involves the careful construction, interpretation, and modification of external representations, such as diagrams as well as physical
and virtual models. In sum, spatial thinking in STEM involves a complex interaction between multiple processes and representations that creates many challenges for college students as they pursue a STEM degree.

Although spatial thinking is clearly ubiquitous in college STEM courses, my own research indicates that spatial thinking (of all kinds) in chemistry and other STEM disciplines is task-specific. That is, throughout a given disciplinary curriculum, student achievement is not solely determined using assessments that directly require reasoning about spatial relationships relevant to the domain. In fact, many assessment items evaluate students on their ability to reproduce declarative knowledge, to interpret and construct disciplinary representations, and to analyze experimental data. To complete such tasks, spatial thinking is not relevant to produce a reasonable problem solution. Given this, outstanding questions remain regarding when spatial thinking is required to understand STEM concepts and how spatial thinking contributes to STEM problem solving.

To that end, much research has been devoted to understanding the causal factors responsible for the challenges STEM students face when engaged with spatial thinking. Although much of this work has demonstrated a relationship between students’ spatial abilities (i.e., mental rotation and spatial visualization), it is my opinion that individual differences in spatial ability only partially account for the success and failure of many students to succeed in STEM. As above, spatial thinking requires more than the simple application of spatial ability to problem solve successfully: even students with high spatial ability struggle in STEM courses at all levels. In my own research, my collaborators and I have shown that both high and low spatial students experience challenges learning to interpret formalisms of disciplinary representations and to apply heuristics to scientific diagrams. Thus, individual differences in spatial ability do not fully explain the variance in student achievement or STEM degree attainment.

Indeed, STEM achievement for high and low spatial ability students can be significantly approved by novel instructional practices. Among these practices are “spatial interventions” that help train students to engage in spatial thinking in the STEM classroom. Importantly, in my own work, my collaborators and I have studied the impact of organic chemistry interventions that not only train students to apply strategies that involve mental imagery, but also interventions that help students learn to apply analytic strategies to decode spatial information in diagrams using disciplinary algorithms. This work has shown that individual differences in spatial ability are less predictive of chemistry achievement than students’ ability to apply trained problem solving strategies. Perhaps more interesting, we have observed that the best achievement among all students, and women in particular, results from interventions that train the synergistic application of disciplinary algorithms and mental imagery when engaged in spatial thinking.

It is clear that spatial thinking in chemistry and other STEM disciplines plays a central role in the college curriculum. Only recently has this role been fully appreciated by STEM researchers and STEM educators, and further research is needed to understand the challenges students face engaging in spatial thinking in general and in each STEM discipline. Importantly, additional research is needed to study the impact of new interventions that aim to improve students’
spatial abilities as well as those interventions that aim to improve representational competence or flexible strategy choice. It is critical that the community of educators recognize the central role of spatial thinking in STEM teaching and learning; however, they must refrain from limiting access to STEM programs to only those students who excel on spatial ability measures. More work is needed to understand how best to support students who all ability levels to succeed in STEM courses.