Research at the Interface of Cognition, Education, and Disciplinary Science

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Overview

Meeting the challenges of the 21st century will require both workers who are highly competent in fields of science and engineering and citizens who have a high degree of science literacy. Accomplishing these goals will, in turn, require changes to undergraduate science and engineering education (National Research Council, 2012). With their expertise in learning, memory, problem solving, and diagrammatic and spatial reasoning, cognitive scientists are ideally situated to make important contributions to this endeavor.

To gain competence in STEM fields, students must learn to engage in two distinct types of reasoning: (a) how to interpret and reason with domain-specific representations such as diagrams of evolutionary trees, digital images showing brain anatomy, and 3-D models of chemistry molecules; (b) how to reason about processes that operate on those structures. For example, a variety of transformational processes (e.g., compression, tension, shear) operate to produce geologic events (e.g., folds, faults). The distinction between structures and processes, as well as the interplay between them, is a core issue in cognitive science.

This symposium, moderated by Novick and Hegarty, includes five talks, by leading experts in their fields, on current research at the interface of cognitive science, education, and other science disciplines. Three talks will consider how cognitive and perceptual principles affect comprehension and learning of science concepts and disciplinary representations. Two talks will examine how investigating representations, reasoning strategies, and science practices broadens our understanding of spatial thinking and reveals previously unrecognized spatial reasoning processes.

Physics

Richard Catrambone will talk about research comparing concept-based and traditional curricula for teaching introductory physics (e.g., Caballero et al., 2012). Physics curricula fail to prepare students for solving basic physics problems. The Matter and Interactions (M&I) curriculum was designed to improve learning by organizing concepts around fundamental principles. “Traditional” course students often learn to use special case formulas. Catrambone and colleagues expected that M&I students would learn to approach problems from first principles, but they have found little evidence of this. M&I students’ think-aloud protocols during problem solving involving the Force Concept Inventory (FCI) indicate that they failed to employ the fundamental principles around which their curriculum was designed. When presented with probes, students answered using the language from their respective (M&I or traditional) courses. While this suggests the courses have some impact, it does not appear to extend to solution procedures. This has implications for claims that courses created around core concepts can successfully lead learners to reason in domain-appropriate ways.

Neuroanatomy

John Pani will talk about research on developing and testing a computer-assisted system for teaching neuroanatomy (e.g., Pani et al., 2014). Neuroanatomy is a core discipline that is perceived to have a high level of difficulty for obtaining even basic expertise. Students must learn to describe a large domain that is complex both in structure and function. Modern digital illustration and computational systems have great promise for reducing the barriers to learning in such a field, and yet progress to date has been disappointing. Pani and colleagues' research in learning neuroanatomy suggests that cognitive science can help to design, test, and develop digital systems that will dramatically improve the educational experience in this area. Pani will review how a variety of design principles, including intuitive exploratory graphics, efficient mapping of organizational frameworks, frequent testing with immediate feedback, and continuous adaptive learning have generated successful instructional systems.

Biology

Laura Novick will talk about research on students' ability to interpret and reason with the information depicted in evolutionary trees (e.g., Novick & Catley, 2013). Diagrams are important cultural tools that are central to conceptual understanding and theoretical development in many scientific disciplines. Contrary to what many people believe, however, diagrams do not transparently convey the intended meaning about the relationships among the concepts being depicted. The elements of which diagrams are composed (e.g., lines, arrows, circles) are meaningful symbols in their own right, and they may suggest interpretations that either support or conflict with the scientifically appropriate interpretation of the diagram. How the human perceptual system works also affects students' interpretations of diagrams. In particular, Gestalt principles of grouping (e.g., good continuation, connectedness) play an important role. Finally, prior experience with a superficially similar task—reading text—affects the meaning that students extract from diagrams. Novick will describe research on how these factors affect undergraduate students' interpretations of tree-of-life diagrams from biology, which depict evolutionary relationships among taxa.

Chemistry

Mary Hegarty will talk about research on how to train spatial intelligence in the domain of organic chemistry (e.g., Stieff et al., 2014). In recent years there has been new recognition of the importance of spatial thinking in science. Spatial visualization ability is related to success in science disciplines and performance on spatial ability tests can be enhanced by training. As a result, current approaches aim to increase science achievement by recruiting individuals with high spatial ability, or by training of general spatial abilities. Hegarty and colleagues' alternative approach is to characterize spatially intelligent activities as they occur in science disciplines and focus on how to train these intelligent activities. Focusing on the domain of organic chemistry, they have found that spatial visualization is just one component of spatial thinking in science. Other components include adaptive strategy choice between imagistic and more analytic thinking, and proficiency in using multiple spatial representations. Based on these insights, and recent intervention studies, Hegarty will discuss how to best nurture spatial thinking in science.

Geoscience

Tim Shipley will talk about research on spatial reasoning in the geosciences (e.g., Resnick & Shipley, 2013). Understanding Earth's physical structure and history requires characterization of 3D solid structures from surface observations, and using the current state of the Earth to reason about the processes that have acted on it in the past. Shipley and colleagues have identified a previously unrecognized visual completion process that allows visualizing interior structures of objects but results in systematic errors inferring 3D forms from single cross-sections. Reasoning about Earth processes requires simulation of both rigid events (e.g., rotation—the traditional subject of mental event simulation research) and non-rigid events (e.g., bending and breaking). Expert geologists excel at visualizing both types of events, whereas expert chemists excel only on rigid rotations. Shipley will discuss these findings and their implications for supporting students as they struggle with spatial challenges in STEM practice and training.

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