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Mental rotation and diagrammatic reasoning in science

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Abstract

This article presents 3 studies that examine how students and experts employ mental rotation and a learned heuristic to solve chemistry tasks that involve spatial information. Results from Study 1 indicate that despite instruction in analytical strategies, students choose to employ mental rotation on canonical assessment tasks. In Study 2, experts were observed to selectively employ analytical strategies for the same tasks. In Study 3, students who used mental rotation were trained to use analytical strategies with equal success. Collectively, the 3 studies address the affordances of alternative strategies in science and the potential role of each in the classroom.

Keywords: Spatial reasoning; Problem solving; Diagrams

1. Introduction

Much of the reasoning done in science is about the dynamics of objects that exist in three-dimensional space. For example, physicists reason about flying balls and spinning gyroscopes and geologists explain topography by constructing models of hidden subterranean structures. Ostensibly, science requires the use of visuo-spatial strategies for such tasks because scientific problems often require explicit consideration of spatial relationships (Gilbert, 2005; Mathewson, 1999): chemists might mentally rotate visualized molecules when designing new pharmaceuticals (Habraken, 1996) and engineers might mentally animate gear trains to analyze mechanical systems (Hegarty, 1992). Likewise, the role of visuo-spatial strategies appears self-evident in the classroom. Correlational data suggest that a science student's ability to engage in visuo-spatial reasoning can be critical for success (Coleman & Gotch, 1998; Pallrand & Seeber, 1984; Schueneman, Pickleman, Hesslein, & Freeark, 1984), and some recent curriculum design efforts aim to support students' use of visuo-spatial reasoning (e.g., Barnea & Dori, 1999; e.g., Wu, Krajcik, & Soloway, 2001).

Despite the ostensible primacy of visuo-spatial strategies, there are reasons to suspect such strategies are mitigated. At all levels, scientific problem solving involves the use of highly specialized diagrams to represent unseen phenomena and spatial relationships. While these diagrams may serve as scaffolds for supporting visuo-spatial strategies, they may also allow the problem solver to obtain and reason about critical spatial information from immediate perceptual processes instead of from mediating internal spatial representations (Hegarty, 2004; Larkin, 1983). That is, students and experts may use specific "rules" for discovering, manipulating and transforming the spatial relationships

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embedded in diagrams without employing visuo-spatial strategies. For example, engineering students have reported that the direction of gear rotation in a mechanical system can be determined without mental animation by applying the rule that "every other gear turns the same way" (Schwartz & Black, 1996). It would seem then that both analytical strategies and visuo-spatial approaches contribute to successful scientific problem solving.

An examination of one task from a typical organic chemistry curriculum illustrates the potential role of both types of problem solving strategies in science. Early during instruction organic chemistry students learn the concept of stereochemistry, which concerns the three-dimensional arrangement of atoms within a molecule. Specifically, students learn that 2 molecules that contain the same atoms with identical bond arrangements may have unique three-dimensional structures: such molecules have the same physical makeup, yet they are unique spatially. For example, both molecules in Fig. 1A contain one atom each of carbon, fluorine, chlorine, bromine, and iodine; however, the molecules are asymmetrical mirror images, or enantiomers, and no imagined rotation of either molecule will allow them to superimpose. In organic chemistry, students solve this and related problems in which they determine whether 2 molecules are identical as well as propose methods to transform one spatial configuration into the other.

Although it is presumed that such problems are solved specifically with mental rotation strategies (Ealy, 1999; Pribyl & Bodner, 1987; Small & Morton, 1983), organic chemists have developed a simple heuristic for analyzing and manipulating these diagrams. Typical organic chemistry instruction teaches one analytical strategy for quickly solving stereochemistry problems without mental rotation. Using this strategy, instructors teach students to first decide whether the diagrams are symmetrical by determining if any of the 4 ligands around the central carbon are identical. If 2 or more are identical, the molecule is symmetrical and will always superimpose upon its mirror image, which is identical, as in Fig. 1B. Using this analytical strategy, students learn to inspect molecular diagrams for symmetry to make judgments about molecular identity without using mental rotation.

Although the use of such visuo-spatial and analytical strategies for problem solving in science and engineering has been documented elsewhere, the availability and acquisition of each strategy during the course of instruction is less clear. For example, studies in mechanical engineering have shown that some students apply analytical strategies as a first strategy on a given task (Cooper, 1988), while others students require extended practice (Schwartz & Black, 1996). Likewise, the trade-offs of using either strategy are ill defined. Whereas visuo-spatial strategies may offer students' a key insight into spatial relationships, analytical strategies may make problem solving more efficient and precise. Indeed, some expert physicists report that they cannot make significant progress on a problem *without* constructing a diagram (Larkin, McDermott, Simon, & Simon, 1980), while others indicate that visualization helps reveal important qualitative information (Qin & Simon, 1992).

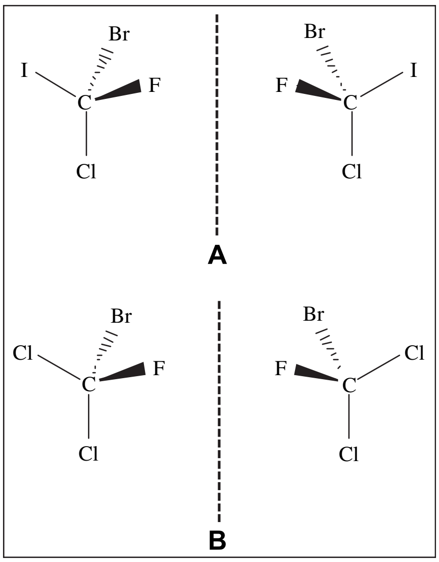

Fig. 1. Sample stereochemistry tasks in organic chemistry. (A) Mirror images of asymmetric molecules are unique. (B) Mirror images of symmetric molecules are identical. Wedges are bonds above the page; dashes are below.