Representational Competence and Spatial Thinking in STEM

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Abstract: Spatial ability predicts success in STEM fields, particularly chemistry. As such, new educational models have called for learning environments that improve spatial ability. These environments neglect the role of representational competence in supporting spatial thinking in individual STEM fields. This short paper reports a preliminary investigation concerning the unique contribution of representational competence to spatial thinking in the discipline of organic chemistry. Using authentic disciplinary tasks we show that student achievement and response time depends more upon their developing representational competence in chemistry than mental rotation ability and that the format of a disciplinary representation can significantly mediate spatial thinking. Given these findings we argue that new learning environments that target representational competence may be more effective at supporting spatial thinking than those that attempt to train generic spatial ability.

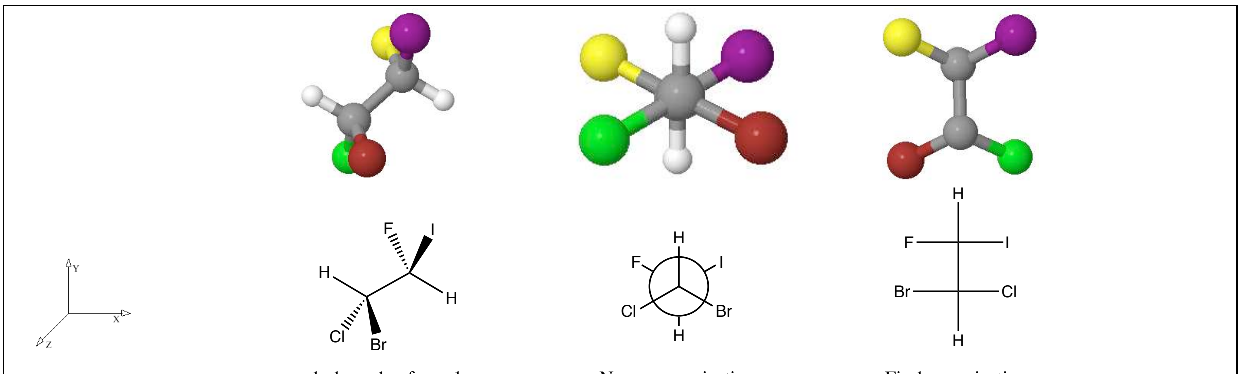
Spatial Thinking in STEM Disciplines

Spatial thinking is a central component of problem solving at all levels of STEM (Science, Technology, Engineering, and Mathematics) instruction (National Research Council, 2006). In both beginning and advanced classrooms, students are tasked with identifying important spatial relationships relevant to scientific concepts and predicting how transformations of those relationships affect physical and biological systems. Spatial thinking ranges in complexity from reasoning about simple geometric relationships, such as the distance between two points on a geologic map, to complex spatiotemporal dynamics, such as reasoning about chemical reaction processes in three-dimensional space. Spatial thinking is challenging and has been cited as a primary barrier to success in STEM classrooms and to entry in STEM careers (Humphreys, Lubinski, & Yao, 1993; Lubinski, 2010; Wai, Lubinski, & Benbow, 2009). Students who struggle with spatial thinking in entry-level STEM courses are less likely to enjoy STEM instruction and pursue STEM professions less frequently (Shea, Lubinski, & Benbow, 2001).

The emphasis on spatial thinking in STEM disciplines suggests that individual differences in spatial ability are related to STEM achievement. Indeed, correlation studies indicate that achievement in several STEM fields is, to some degree, dependent on spatial ability, such as mental rotation and perspective taking (Kozhevnikov, Hegarty, & Mayer, 2002; Pribyl & Bodner, 1987; Sorby, 2009; Turner & Lindsay, 2003). Many STEM achievement assessments require students to visualize the spatial transformation of complex structures, mentally rotate imagined objects to compare spatial features, and assume imagined perspectives to draw two-dimensional diagrams from different orientations. Thus, students who score poorly on several spatial ability measures (e.g., mental rotation, perspective taking, or spatial visualization) are seen to perform poorly in STEM fields that emphasize spatial reasoning (Shea et al., 2001).

The primacy of spatial thinking in the STEM classroom has given rise to a body of learning environments that attempt to support and train spatial thinking in different disciplinary contexts. These studies are quite diverse in their goals and design principles. Designs range from those that attempt to train basic visuo-spatial ability skills through sustained practice (Miller & Halpern, in press; Sorby, 2001) to those that scaffold spatial thinking with concrete and virtual models (Stull, Barrett, & Hegarty, 2013; Stull, Hegarty, Dixon, & Stieff, 2012). These efforts have yet to result in large improvements in STEM achievement or degree attainment, although several individual designs show promise for improving spatial thinking in general and on specific tasks (Uttal et al., 2013). As such, curricular and instructional designs that aim to improve spatial thinking in STEM disciplines remain important targets of current reform efforts.

Despite the correlation between spatial ability and STEM achievement, it is not clear if spatial ability is the primary factor that determines success in STEM achievement. Recent studies suggest that student success in STEM fields is partially dependent upon representational competence (Kozma & Russell, 1997; Stieff, 2011; Stull et al., 2012) and discipline-specific problem solving strategies (Schwartz & Black, 1996; Stieff, 2007; Stieff, Hegarty, & Dixon, 2010). Representational competence comprises a set of skills that include the ability to analyze features of a representation, transform one representation into another, generate novel representations, explain the utility of a given representation, and explain the unique affordances of different representations (diSessa & Sherin, 2000; Russell et al., 1997). These skills are necessary for students to interpret and relate the wide variety of external representations across STEM domains that highlight or mask spatial information to varying degrees. For example, Figure 1 depicts an example assessment item from organic chemistry that requires students to translate from a *dash-wedge perspective formula* to a *Newman projection* to identify high and low energy spatial conformations of an organic molecule. Students' with limited representational competence who are unable to perform the initial translation are unlikely to identify how the different spatial conformations correlate with energy (Raje & Stieff, 2009, April). Innovative learning environments that aim to improve representational competence may constitute more productive avenues to support student success than those that emphasize generic spatial thinking. The skills composing representational competence reflect authentic disciplinary practices and ways of knowing not addressed by an environment that emphasizes abstract spatial thinking.



dash-wedge formula Newman projection Fischer projection

Figure 1. The dash-wedge, Newman, and Fischer representations each use different formalisms to represent the same three-dimensional information in two-dimensional diagrams. In the figure, a concrete molecular model of (*1S*, *2R*)-1-bromo-1-chloro-2-fluoro-2-iodoethane has been spatially transformed to align with each respective diagram. The model depicted here uses colors to represent individual elements, which are represented symbolically in the diagrams. Grey = carbon (C), white = hydrogen (H), green = chlorine (Cl), brown = bromine (Br), yellow = fluorine (F) purple = iodine (I).

Present Study

In this investigation we explore the relationship between spatial ability and representational competence in an experimental study of spatial thinking in the STEM discipline of organic chemistry. Arguably, organic chemistry emphasizes spatial thinking more so than any other post-secondary STEM course, as the discipline's overarching learning objectives include identifying spatial relationships in hydrocarbons and explaining the chemical and physical properties of a compound resulting from molecular structure. To investigate the relationship between spatial ability and representational competence we compared student achievement on three assessments that varied by representational format. Formats included (1) only three-dimensional models that made spatial relationships salient using shading and perspectival cues (3D-Model), (2) only two dimensional diagrams that made spatial relationships implicit using disciplinary formalisms (2D-Diagram), and (3) mixed formats that include multiple representations of a molecular structure (2D-3D Mixed). Each assessment was constructed of items that required students to make similarity judgments about pairs of molecular representations to determine whether each pair represented the same molecule or a mirror image (i.e., enantiomeric relationship). Such items are authentic assessment items employed in organic chemistry classrooms to evaluate student knowledge of stereochemistry (Stieff, 2007). Using accuracy and response time data we predicted that student achievement would be higher on the assessments that included a single representation whether a 3D-Model or a 2D-Diagram than on the mixed representation assessment. Conversely, we predicted that response time would be higher on the mixed representation assessment. We base these predictions on the assumption that representational competence, as opposed to spatial ability, is the primary barrier to spatial thinking in the STEM disciplines. In other words, student failure will result from challenges relating multiple representations of spatial information independent of their mental rotation ability.

Method

Participants

Twenty-eight (16 female) undergraduate chemistry students participated on a volunteer basis. Each participant was recruited from the population of students who had completed at least five weeks of instruction in organic chemistry at a major research university. All students had received instruction in content assessed in the study.

Instruments

Three tests of mental rotation that varied by the included representation (3D-Model, 2D-Diagram, 2D-3D Mixed) were constructed and employed (see Figure 2 for examples). Each test included stimuli that consisted of pairs of molecular representations that were either identical or mirror image reflections. Each test contained six asymmetrical stimuli rotated in the picture plane. Identical object pairs were presented once at five unique angles ranging from 0 to 180 degrees in 45-degree increments. Six mirror-reflected object pairs were presented at three randomly selected angles ranging from 0 degrees to 180 degrees in 45-degree increments. Thus, each test included 48 trials. The design was not balanced with regard to mirror image pairs, which were not analyzed: Such pairs were included to prevent participants from assuming that all pairs were identical. Mental rotation was evaluated by the Vandenberg Test of Mental Rotation (Vandenberg & Kuse, 1978).

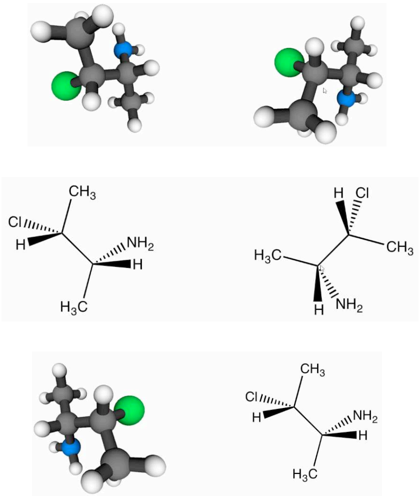


Figure 2. Example stimuli: From top to bottom: 3D-Model, 2D-Diagram, and 2D-3D Mixed item.

Procedure

The study utilized a repeated-measures design with representational format (2D vs. 3D vs. 2D-3D) as a within-subjects variable. All participants completed all blocks with each block randomly presented first. The experiment was presented with ePrime v.2.0. First, participants viewed a screen instructing them to compare stimuli pairs to determine whether each pair contained identical structures. Participants cued the presentation of each stimulus by pressing ‘‘SPACE” and responded that pairs contained identical objects by pressing ‘‘I’’ or pressing ‘‘E’’ if they were mirror images (or enantiomers). Participants completed 6 practice trials followed by 144 experimental trials. All participants completed each test in approximately 30-40 minutes during which the keyed response time from stimulus onset was recorded for each trial. The mental rotation test was then administered. Participants received $20 USD.

Results

First, accuracy was calculated as the average number of correct similarity judgments on identical pairs and analyzed via repeated-measures ANOVA with representational format as the within-subjects variable controlling for mental rotation ability. A main-effect of representational format ($F(2,26) = 28.9$, $p < .001$, $\eta_p^2 = .53$) and spatial ability ($F(2,26) = 8.70$, $p = .007$, $\eta_p^2 = .25$) was observed. As illustrated in Figure 3, planned contrasts revealed that students performed worst when evaluating 2D-3D Mixed Representations ($M = .77$, $SD = .15$) than they did evaluating 3D-Models ($M = .89$, $SD = .07$, $F(1, 26) = 8.7$, $p = .007$, $\eta_p^2 = .25$) or 2D-Diagrams ($M = .83$, $SD = .15$, $F(1,26) = 8.51$, $p = .007$). There was no difference in accuracy between 2D and 3D conditions, $F(1,26) = 1.96$, $p = .17$. Second, response time was calculated as the average time to respond to a stimulus pair and compared across assessments as above. A significant main effect of representational format was observed ($F(2,27) = 136.68$, $p < .001$, $\eta_p^2 = .73$) but no relationship between spatial ability and response time was evident ($F(2,26) = .51$, $p = .48$). As illustrated in Figure 4, planned contrasts revealed that students responded slower to 2D-3D Mixed Representations ($M = 17853$ms, $SD = 5068$ms than to either 3D-Models ($M = 8764$ms, $SD = 3395$ms, $F(1,26) = 64.2$, $p < .001$, $\eta_p^2 = .71$) or 2D-Diagrams ($M = 10759$ms, $SD = 4018$ms, $F(1,26) = 136.7$, $p < .001$, $\eta_p^2 = .835$).

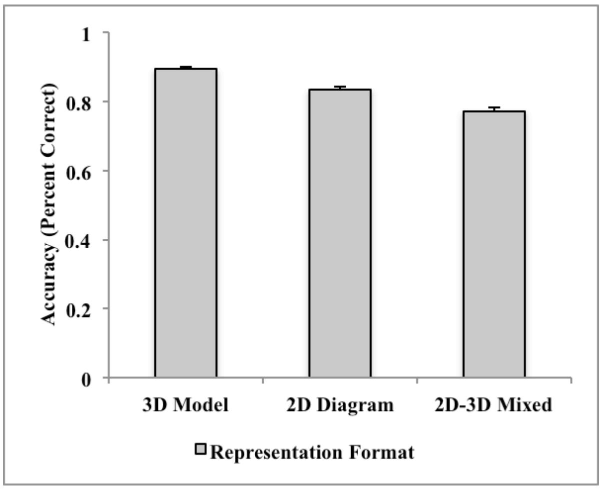


Figure 3. Participant accuracy across conditions. Student achievement was significantly higher in the 3D-Model condition than each of the other two conditions. Performance was lowest in the 2D-3D Mixed condition.

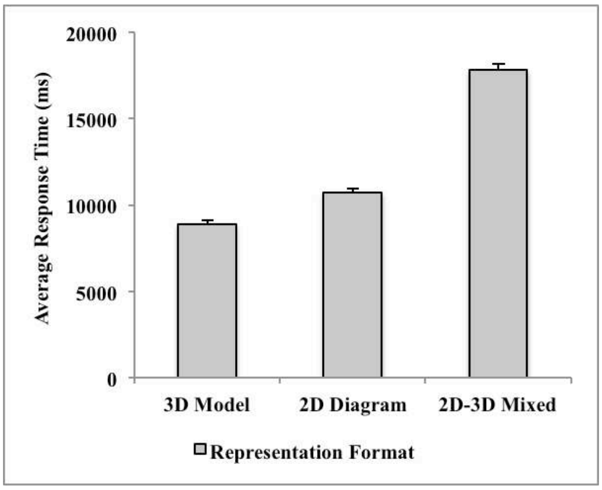


Figure 4. Participant response time across conditions. Response time was significantly higher in the 2D-3D Mixed condition than each of the other two conditions. Performance was lowest in the 3D-Model condition.

Conclusions

These results are consistent with our initial predictions that students would perform better and faster when comparing representations with similar formats (2D, 3D) than those with mixed formats (2D-3D). As above, all students were highly accurate in their evaluation of identical pairs; a meaningful decrement in performance was observed only for assessment items that contained mixed representational formats. Ostensibly, this increase in response time reflects the additional processing demands required to translate between representations to make an identity judgment. Finally, although mental rotation ability correlated moderately with achievement, the results suggest that this correlation depends upon how salient spatial information appears in disciplinary representations. Indeed, our analysis revealed that the format of the disciplinary representations explained more than twice the variance in achievement than spatial ability. Thus, these results suggest that mental rotation *and* representational competence are necessary to solve mixed format items. This result is consistent with prior research that has demonstrated the task-specificity of strategy use (Stieff, 2007) and suggests that future learning environments that target representational competence may be more effective at supporting spatial thinking in STEM disciplines than those that attempt to train generic spatial ability in isolation.

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