The Role of Gesture in Solving Spatial Problems in STEM

Matthew E. Lira, Mike Stieff, Stephanie Scopelitis, University of Illinois at Chicago, 1007 W. Harrison Street,
Suite 2048; Chicago, IL 60607
Email: mlira2@uic.edu, mstieff@uic.edu, scopelitis@gmail.com

Abstract: Gestural activity is an important component of teaching and learning in STEM disciplines. Gestures are most often observed in social settings where two or more interlocutors are engaged in natural conversation. Empirical investigations, however, suggest that gestures also play a role in individual cognition. We conducted two experiments that investigated the functional role of gestures as a strategy for solving translation problems in organic chemistry. Gestured-instructions did not promote gesture-use as a strategy. Removing instructional diagrams from view did promote gesture use. Students who did gesture did not perform better than those who did not; however, students who received gestured-instructions appeared more likely to adopt the spatial perspective of the instructor.

General Introduction

Gestural activity is an important component of teaching and learning in STEM (Science, Technology, Engineering and Mathematics) disciplines (Alibali & Nathan, 2007; Radinsky, 2008; Roth, 2000). The role of gestures to support communication and meaning making in STEM is most often observed in social settings where two or more interlocutors are engaged in natural conversation. Empirical investigations suggest that gestures also play a role in individual thinking (Rauscher, Krauss, & Chen, 1996; Roth & Hwang, 2006), learning (Goldin-Meadow, Alibali, & Church, 1993), and problem-solving (Hegarty, 2004; Schwartz & Black, 1996). Moreover, gestures can function pedagogically (Ehrlich, Levine, & Goldin-Meadow, 2006) by augmenting reasoning and problem-solving. Recent studies investigating the functional role of gesture in tasks such as mental rotation (Chu & Kita, 2011), mathematical equation solving (Alibali & Goldin-Meadow, 1993), Piagetian conservation tasks (Church & Goldin-Meadow, 1986), Tower of Hanoi tasks (Garber & Goldin-Meadow, 2002), and gear-rotation tasks (Perry & Elder, 1997) suggest that gesture not only supports communication, but also plays an important role in individual cognition.

Although not a primary focus of analysis in studies of individual gesture use, one feature common to the problem-solving tasks in these studies is that each involves reasoning about dynamic, spatial-relational information. Gestures are complex motor movements that occur in 3-dimensional space. Importantly, gestures afford the individual the ability to represent dynamic, spatial-relational information with the hands. Indeed, the history of gesture analysis suggests that gestures convey the "imagistic component" of thought (McNeill, 1996; McNeill, 2005). Theoretically, then, when an individual displays gestures while problem solving it offers evidence that imagistic reasoning is used as the primary problem-solving strategy (Stieff, 2011; Stieff & Raje, 2010). Nevertheless, the precise functional role of gesture in problem solving remains unknown. For example, gesture use may allow the problem solver to offload spatial information onto the hands and thus free up cognitive resources (Goldin-Meadow, Nusbaum, Kelly, & Wagner, 2001). Alternatively, gestures may cue visual or motor schema that provide important insights into spatial relationships. Then again, gestures may be epiphenomenal and simply indicate that other unseen processes are at work.

The present study offers initial insight into the functional role of gesture in spatial problem solving in a STEM discipline. Specifically, we present our first efforts to understand the effect of gesture use on solving representational translation problems, or translations between molecular diagrams, in organic chemistry. Organic chemistry is a domain heavily focused on the study of spatial relationships in molecules and is an opportune discipline to study the role of gesture use during individual problem solving. As part of the course of study in organic chemistry, students must learn to represent three-dimensional structures with two-dimensional diagrams, such as Dash-wedge, Newman, and Fischer Projections (see Figure 1). To successfully translate between these diagrams, students must attend to the precise way that each diagram depicts spatial-relational information differently. Previously, Stieff and colleagues (Stieff, 2011; Stieff & Raje, 2010; Stieff, Ryu, & Dixon, 2010) showed that self-reports of using imagistic strategies to solve such problems occur contemporaneously with the use of spontaneous gestures *during* problem-solving activities. In the present study, we examined whether gestured problem-solving instructions can (1) improve students' achievement on translation tasks and (2) increase students' use of gestures (and presumably imagistic reasoning strategies) during problem solving.

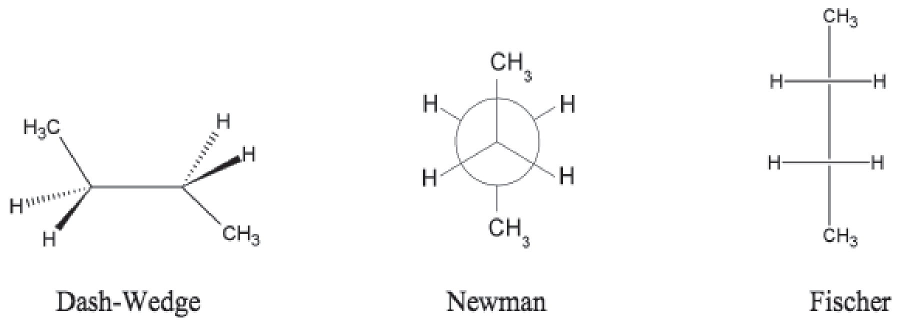

Figure 1. Three commonly used molecular diagrams representing different perspectives on the same molecule.

Methods & Analysis

We conducted two experiments that investigated the functional role of gesture in problem-solving. In the first experiment, we recruited 20 participants enrolled in either a first- or second-semester undergraduate organic chemistry course. Participants were randomly placed into one of two groups: No Gesture Instructions (NG) or Gestured Instructions (G). In the NG-group (10 participants), problem-solving instructions and short explanations of each depicted diagram were presented via written text and diagrams only. Students were asked to read the directions/explanations on their own, and the instructions and accompanying images were made available to NG-group participants during problem solving. In the G-group (10 participants), the same instructions and explanations were presented by the experimenter via talk and gestures, which were produced over the relevant molecular diagrams presented on an 8.5” × 11” page (see Figure 2). Instructional gestures were based on gestures observed in use by organic chemistry lecturers teaching at the participants’ university. The molecular diagrams were made available to participants during problem solving, but the written instructions were removed. Following instruction, participants in both groups completed an 18-item organic chemistry representation translation assessment. Each item presented one representation (Fischer, Newman or Dash-wedge) of a molecule and instructed the student to draw the molecule using one of the other two representations. Upon completing the assessment, participants were debriefed, paid $20 USD, and dismissed.

Figure 2. An example of a “modeling” gesture used during instruction.

In the second experiment, we followed a similar method with 24 additional participants (12 NG-group, 12 G-group). Here, we altered the protocol by removing the molecular diagrams after providing instructions and explanations to examine how the availability of the diagrams affected gesture production and achievement.

For this analysis, we exclusively coded the problem-solving segments and did not analyze instances of instruction or debrief. Videos were reviewed for instances of gestural activity and instances related to *depiction* were identified. A single instance of gestural activity was defined as the time from which the hands first engaged in gesturing to the time they came to rest. We define depictive gestures to include all gestural actions that invoked representations of an object or idea, such as molecular shape or structure. For example, participants could use their hands to depict a molecule by extending two fingers to invoke nearby bonds as in Figure 2. Similarly, participants could simulate performing an action upon a referent, such as “grabbing” a depicted bond and rotating it clockwise. We did not analyze personal (e.g., face-scratching), deictic (e.g., pointing at the paper or diagram), or pre-writing (e.g., tracing a structure on the paper) gestures. Coded gestures were labeled either “gross” or “subtle”; gross refers to large, full hand actions and subtle refers to small, abbreviated actions.

Student responses to each assessment item were coded as *absolutely* or *relatively* correct. Absolutely correct responses included only those drawings that rendered the molecule in the exact spatial perspective and conformation as it was presented in the given diagram. Relatively correct responses included any drawing that preserved the correct internal spatial-relations, but did not render the exact spatial perspective and conformation of the given diagram. For example, a relatively correct response might include drawings of the correct molecule rotated 180 degrees. Additionally, each response was coded for *directionality*, *orientation*, and *conformation*. In terms of directionality, responses were coded as rendered from the left or right depending upon the given diagram. In terms of orientation, responses were coded as rendered as right-side-up or upside-down. In terms of conformation, responses were coded as rendered with all internal spatial-relationships preserved as in the given diagram or modified. Importantly, the gestures produced by the interviewers were systematically presented *from a right-side directionality with a right-side up orientation* toward the given diagrams.

Results and Discussion

First, we address the question, "Does gestured instruction improve achievement?" Based on prior research involving the functional role of gesture during problem solving, we predicted that gestured instruction would improve achievement on the representational translation task. In addition, we are also able to examine the interaction of diagram availability and gestured instructions on achievement because we manipulated the availability of molecular diagrams across experiments. Because the instructional diagrams depict important spatial relationships between each representation, we predicted that achievement would be higher when diagrams are made available. To test these predictions, we analyzed the total number of correct items via a 2 (Gestured Instruction, No Gesture Instruction) x 2 (Diagrams Available, Diagrams Removed) ANOVA. The analysis revealed that there was no effect of instruction, $F(1, 44) = .32$, $p = .27$, or diagram availability, $F(1, 44) = .13$, $p = .72$, on achievement. Additionally, no interaction was observed.

We next asked, "Does students' gestural activity increase or decrease after gestured instructions?" As above, we were again able to examine the effect of diagram availability on students' gesture use. To answer this question we analyzed the total number of gestures produced by students via a 2 (Gestured Instruction, No Gesture Instruction) x 2 (Diagrams Available, Diagrams Removed) ANOVA. The analysis revealed that there was no main-effect of gestured instruction, $F(1, 34) = .98$, $p = .33$. We did, however, observe a main-effect of diagram availability, $F(1, 34) = 4.7$, $p = .04$. As seen in Figure 3, removing the diagrams from view did produce more gestural activity by students.

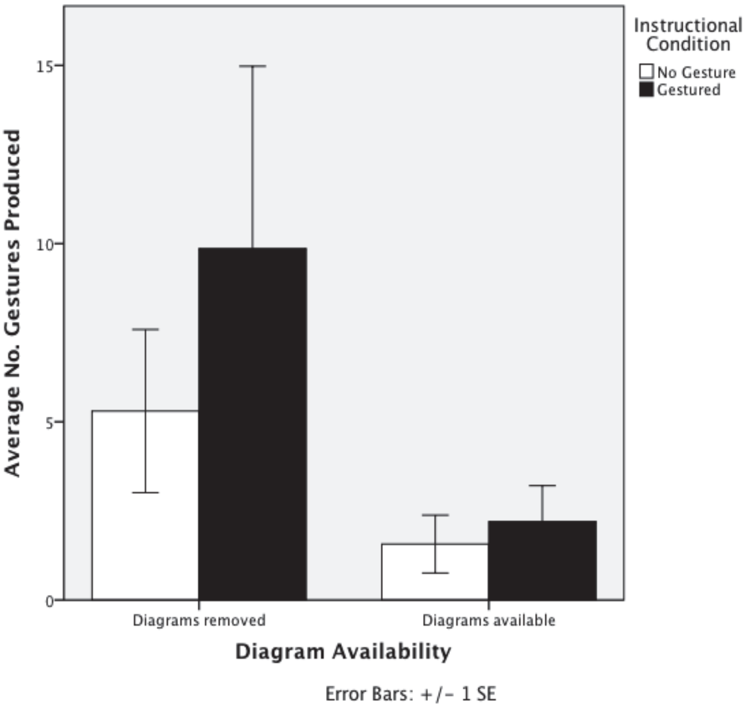

Figure 3. Participants' mean number of gestures by instructions and diagram availability.

As a follow up to both questions, we explored the relationship between individual gesture use and achievement. Achievement was equivalent between those students who used at least one gesture and those who produced no gestures at all during problem-solving, $F(1, 34) = .67$, $p = .42$. Among students who did gesture during problem-solving, however, a moderate correlation was observed between gesture use and achievement that is likely driven by three outliers who produced extremely high numbers of gestures during problem-solving, $r(23) = .58$, $p = .004$.

Given that our instructional manipulation did not improve achievement or increase gestural activity during problem solving, we further examined the possible effect of our instructional conditions on the quality of diagrams produced by participants. Recall that the gestures produced by the interviewers during instruction always depicted a right-hand direction and right-side-up orientation toward the molecular diagrams. Specifically, we were interested in knowing whether participants were more likely to adopt an instructor's perspective when learning from gestures. First, we examined the directionality of drawn structures as above. Interestingly, we observed a trend in the dataset that did not meet statistical significance at alpha = .05: a greater number of "right-side approach" diagrams were observed when instructions were accompanied by gesture, $F(1, 43) = 2.34$, $p = .10$ (see Figure 4). Although gestured instructions produced no observable increase in gesture use or achievement, it did appear to affect the students' perspective when drawing molecular diagrams even in a study with low N, as here.

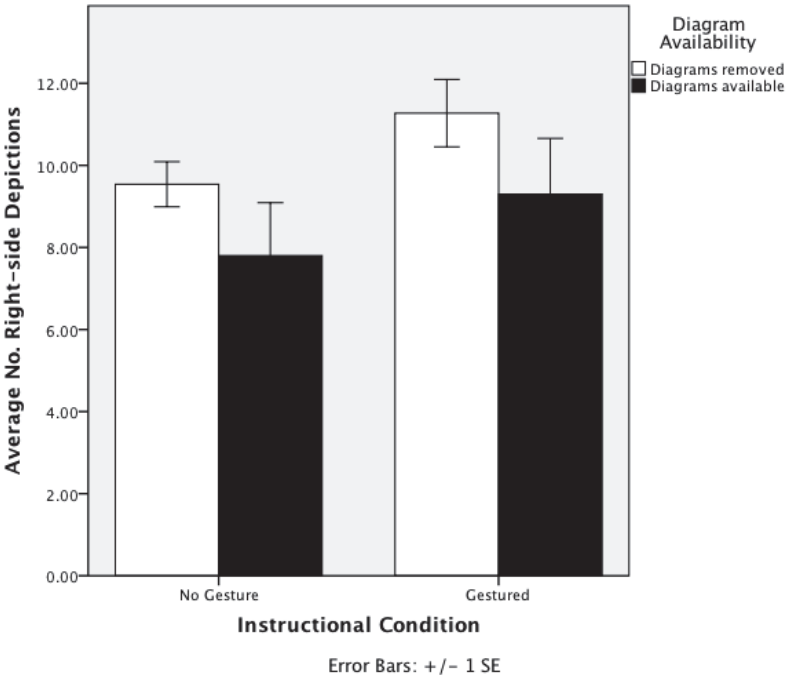

Figure 4. Participants' mean number of right-side depictions by instructions and diagram availability.

Scholarly Significance & Implications

Previous investigations have demonstrated that gestures maintain spatial imagery during communicative activities (Wesp, Hesse, Keutmann, & Wheaton, 2001). Our investigation suggests that this previous finding may extend to contexts in which individuals are reasoning about spatial-relationships in isolation. Moreover, our results indicate an important interaction between gesture use and external representations. That is, individuals appear to use gestures to represent spatial information when external representations of that information are unavailable. Here we observed that when such diagrams are removed from sight, students produced significantly more gestures than when the diagrams were made available. However, many students used gestures while problem solving in an idiosyncratic fashion across experiments. Some participants gestured infrequently, some gestured frequently, and still others gestured randomly during the experiment. Of note, the highest achieving students were observed to produce the largest number of gestures on nearly every task.

Despite the increased gestural activity in the diagrams removed condition, we did not observe a large effect of gesture use on achievement across conditions. Given that we observed a moderate correlation between gesture use and achievement, it nevertheless remains a possibility that increased gesture use may improve achievement. In this investigation, we observed an appreciable amount of variance in gesture production and it may be that participants did not produce a sufficient amount of gestures to support problem solving. Participants may have not produced gestures for several reasons, one being that they have pre-existing strategies for solving translation problems, as has been documented elsewhere (cf., Stieff & Raje, 2010), which they favored over the strategy presented during instruction. As it stands, these results suggest that our instructional intervention may not have been robust enough to encourage students to use gestures during problem solving, which warrant future investigations that include more extensive interventions.

References

Alibali, M.W. & Goldin-Meadow, S. (1993). Gesture—speech mismatch and mechanisms of learning: What the hands reveal about a child's state of mind. *Cognitive Psychology, 25*, 468-523.

Alibali, M. W., & Nathan, M. J. (2007). Teachers' gestures as a means of scaffolding students' understanding: Evidence from an early algebra lesson. *Video Research in the Learning Sciences. Mahwah, NJ: Erlbaum,*

Chu, M., & Kita, S. (2011). The nature of gestures' beneficial role in spatial problem solving. *Journal of Experimental Psychology: General, 140*(1), 102-116.

Church, R.B, & Goldin-Meadow, S. (1986). The mismatch between speech and gesture as an index of transitional knowledge. *Cognition, 23*, 43-71.

Ehrlich, S. B., Levine, S. C., & Goldin-Meadow, S. (2006). The importance of gesture in children's spatial reasoning. *Developmental Psychology, 42*(6), 1259.

Garber, P., & Goldin-Meadow, S. (2002). Gesture offers insight into problem-solving in adults and children. *Cognitive Science, 26*(6), 817-831.

Goldin-Meadow, S., Alibali, M. W., & Church, R. B. (1993). Transitions in concept acquisition: Using the hand to read the mind. *Psychological Review, 100*(2), 279.

Goldin-Meadow, S., Nusbaum, H., Kelly, S. D., & Wagner, S. (2001). Explaining math: Gesturing lightens the load. *Psychological Science, 12*(6), 516.

Hegarty, M. (2004). Mechanical reasoning by mental simulation. *Trends in Cognitive Sciences, 8*(6), 280-285.

McNeill, D. (1996). Hand and mind: What gestures reveal about thought. *University of Chicago Press.*

McNeill, D. (2005). Gesture and thought. *University of Chicago Press.*

Perry, M., & Elder, A. D. (1997). Knowledge in transition: Adults' developing understanding of a principle of physical causality* 1,* 2. *Cognitive Development, 12*(1), 131-157.

Radinsky, J. (2008). Students' roles in group-work with visual data: A site of science learning. *Cognition and Instruction, 26*(2), 145-194.

Rauscher, F. H., Krauss, R. M., & Chen, Y. (1996). Gesture, speech, and lexical access: The role of lexical movements in speech production. *Psychological Science, 7*(4), 226.

Roth, W. M. (2000). From gesture to scientific language. *Journal of Pragmatics, 32*(11), 1683-1714.

Roth, W. M., & Hwang, S. W. (2006). On the relation of abstract and concrete in scientists' graph interpretations: A case study. *The Journal of Mathematical Behavior, 25*(4), 318-333.

Schwartz, D. L., & Black, J. B. (1996). Shuttling between depictive models and abstract rules: Induction and fallback. *Cognitive Science, 20*(4), 457-497.

Stieff, M., & Raje, S. (2010). Expert algorithmic and imagistic problem solving strategies in advanced chemistry. *Spatial Cognition and Computation*, *10*(1), 53-81.

Stieff, M., Hegarty, M., & Dixon, B. L. (2010). Alternative strategies for spatial reasoning with diagrams. In A. K. Goel, M. Jamnik, & N. H. Narayanan (Eds.), *Diagrammatic Representation and Inference.* (pp. 115-127). New York: Springer.

Stieff, M. (2011). When is a molecule three dimensional? A task-specific role for imagistic reasoning in advanced chemistry. *Science Education, 95,* 310–336.

Wesp, R., Hesse, J., Keutmann, D., & Wheaton, K. (2001). Gestures maintain spatial imagery. *American Journal of Psychology, 114*(4), 591-60

Acknowledgement

The preparation of this paper was supported by the National Science Foundation, NSF Award #0723313 (UMD). We would like to gratefully acknowledge Lianne Schroeder for her assistance with data collection and data analysis.