Designing for Spatial Thinking in STEM: Embodying Perspective Shifts Does Not Lead to Improvements in the Imagined Operations

Dane DeSutter, University of Illinois-Chicago, ddesut2@uic.edu
Mike Stieff, University of Illinois-Chicago, mstieff@uic.edu

Abstract: Few studies have sought to test whether embodied learning environments produce learning gains on par with more traditional instruction using controlled comparisons. This paper reports on an experimental investigation of an embodied molecular visualization in organic chemistry aiming to teach students about the spatial concept transformation. The study compared two groups: one group received spatial training instruction on transformation with embodied actions in the molecular visualization environment and a control group observed video captures from the same visualization. Comparisons of pre-/post- scores on mental rotation of molecular stimuli pairs showed no difference between the groups on ability to transform molecules post-intervention. We discuss possible explanations for the failure to observe learning in the present study and suggest possible gaps in embodied theory, namely around considering timescales of spatial learning and how embodied learning may interfere with prior conceptions.

Introduction

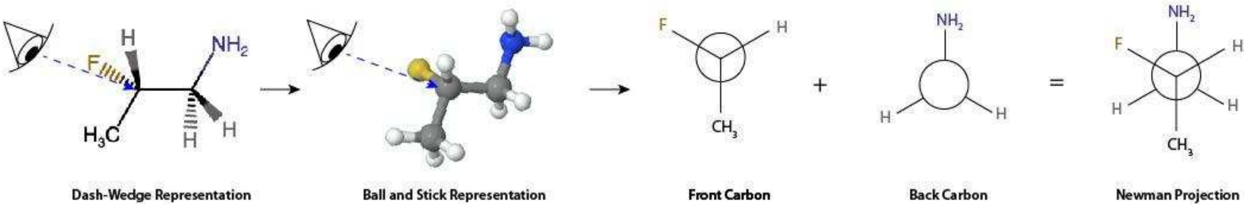
Learning environments designed to support embodied cognition in STEM (Science, Technology, Engineering, and Mathematics) disciplines are of increasing interest in the Learning Sciences design community. Among the various theories of embodied cognition is the view that embodiment is fundamentally a brain-based phenomenon whereby mental representations are grounded in body-based simulation of prior experience (Barsalou, 2008; Wilson, 2002). This view argues that humans readily—and often automatically—reactivate prior sensory and action states via *simulation* to organize their thinking through a specific activity or task. Such experiences can be recalled as a function of task demands to structure information and draw inferences. This view, also referred to as grounded cognition (Barsalou, 2008), proposes that everything from memories, to concepts, to more coordinated activity like problem solving differentially activate mental simulation of stored perception and action states that support sensemaking. This view of cognition also suggests mechanisms through which learning occurs. In particular, learning should best be facilitated when students engage in perceptual and motor activities that help them bridge between abstract disciplinary ideas and concrete, simulable experiences. Learning environments should therefore be designed to facilitate specific multi-sensory experiences that have learners map concrete perception and motor actions to conceptual entities to be learned.

The implications of this view has made it particularly fruitful in the design of learning environments to support spatial thinking (DeSutter & Stieff, 2017) and aspects of numeracy like proportional reasoning (Howison, Trninic, Reinholz, & Abrahamson, 2011). Consequently, various design principles and design frameworks have been proposed to create learning environments that both improve learning in a variety of fields and provide a context to investigate the role that embodied actions play in learning (Abrahamson, Andrade, Bakker et al., 2018; DeSutter & Stieff, 2017; Lindgren & Johnson-Glenberg, 2013). The resultant designs share a similar goal to connect learners' perceptuomotor experience to disciplinary ideas in ways that promote conceptual change and problem solving. Highly varied, these designs have been used to teach a wide range of topics from improving understanding of mathematics (Howison et al.), geometric proofs (Nathan & Walkington, 2017), predator-prey dynamics (Andrade, Danish, & Maltese, 2017), planetary gravitation (Lindgren, Tscholl, Wang, & Johnson, 2016), centripetal force (Johnson-Glenberg, Megowan-Romanowicz, Birchfield, & Savio-Ramos, 2016), and intermolecular forces (Zohar & Levy, 2018).

Despite the unique contexts of these learning environments, each embeds a few common design principles. First, each design scaffolds learners' use of gesture (as well as broader body posture) to represent some aspect of a core concept of the discipline with high fidelity motoric action. The second shared design principle, and of particular interest in this study, is the use of a computer visualization to connect learners' physical actions to the same disciplinary idea. Computer visualizations provide rich representational content that can be highly tailored. Compellingly, the use of various human computer interfaces can sync physical experiences to perceptual experiences not limited by a learners' immediate material environment. Indeed, each of the cited designs uses a (multi)representational display to mediate the relationship between learners' performed physical actions to abstract disciplinary representations. This prior work demonstrates that although the design space is broad, learning has been documented in digital embodied designs under a variety of conditions and STEM domains.

To date, studies investigating the effectiveness of embodied designs for improving STEM learning outcomes have relied primarily on generating qualitative observations of students learning with such designs (e.g., Howison et al., 2011) or using specific competence-based rubrics to measure change (e.g., Andrade et al., 2017). Data included in these studies are typically derived from field observations or think aloud protocols that include a small sample of learners. Such work has significantly advanced detailed accounts of how embodied designs dynamically alter learning and problem solving strategies and further specified the role of embodied activities to support learners. Notably absent from this work, are studies that attempt to compare the differential benefit of embodied designs for supporting learning relative to alternative designs that include visualizations without component embodied activity. While it is clear that embodied designs provide an important context to study learning processes, it is not clear whether these environments have a lasting impact on learners' strategy use or produce benefits in learning outcomes.

In this paper, we explore the differential impact of an embodied learning environment to alter students' problem solving strategies and to improve their learning outcomes in the domain of organic chemistry. Organic chemistry is an ideal STEM context in which to investigate whether embodied designs can promote learning given the discipline's emphasis on spatial concepts and spatial transformations. Within the first weeks of the organic curriculum, students learn to construct common structural diagrams of molecules. These diagrams encode spatial information—equivalent structural diagrams are related to one another through spatial transformations. For example, students are taught to construct Newman projections from Dash-Wedge representations of a molecule as an "end-on" view of a molecule. Organic textbooks instruct students to use a perspective shift to "look" at a molecule from a end-on vantage point to "see" the Newman projection. This instruction is often accompanied by diagrams that use an eye to establish this reference frame relative to that of the reader (see Figure 1). This operation is challenging because it asks a learner to transform implicit spatial cues into a working 3D spatial representation like a Ball and Stick model, extract relative spatial relationships from the assumed viewing angle, and then generate a novel representation from that new vantage point. This is further complicated by the underlying spatial visualization process—perspective-taking—being especially difficult for learners and potentially subject to individual differences in learners' spatial ability (Stieff, Dixon, Ryu, Kumi, & Hegarty, 2014).



Dash-Wedge Representation

Ball and Stick Representation

Front Carbon

Back Carbon

Newman Projection

Figure 1. Example of perspective-taking in the organic curriculum. An eye establishes a frame of reference, from which hydrogen (H) points to the top right, fluorine (F) to the top left, and methyl (CH_3) down on the front carbon. Front and back carbons combine into the Newman projection on the right.

Here, we present the results of an experiment that investigated whether student understanding of *spatial transformation*, specifically perspective-taking, in chemistry can be scaffolded through instruction with embodied actions in a digitally mediated environment. To do this, we compared the learning outcomes and self-reported strategy use of students who learned about perspective-taking in organic chemistry using either an embodied molecular visualization environment or watched instructional videos. We analyzed our data to address the research questions: (1) To what extent does an embodied software visualization controlled via bodily actions promote understanding of transformation? (2) What strategies do students report using to solve transformation items? Given the prior research demonstrating improved learning with embodied interfaces, we predicted that participants learning from the embodied design would display improved learning gains compared to participants in an alternative condition that did not involve embodied design.

Method

Participants

Participants (*n* = 104) were recruited from the population of students who had completed at least one semester of university chemistry at a Midwestern research-extensive university. Students were recruited from Fall 2017 and Spring 2018.

Materials

Academic achievement. Academic achievement was collected to control for potential individual differences in academic achievement, we included students' self-reported GPA.

Spatial ability. Measured using the Peters et al. (1995) mental rotation test. This individual differences measures was collected based on prior research suggesting a relationship between students' mental rotation skill relates to their performance on perspective taking tasks in chemistry (Stieff et al., 2013).

Chemistry learning outcomes. Perspective-taking in organic chemistry was measured using a 16-item instrument that employed three-dimensional representations of organic molecules undergoing transformation around a spatial axis. Each item depicted side-by-side representations of identical or mirror image molecules rotated around either the *x*-, *y*-, *z*-, or an axis in the *xy*-plane by +90º. An angular disparity of 90º was chosen because error rates have been shown to increase linearly as a function of the angular disparity (0º = easiest, 180º = hardest) (e.g., Wright, Thompson, Ganis, Newcombe, Kosslyn, 2008). Thus, these test items are in the mid-range of difficulty. Half of all stimuli pairs were distractors (mirror image). Participants were directed to mentally imagine reversing the transformation of one of the molecules in the pair and compare whether the molecules were a match (identical) or mismatch (mirror image). Test items were counterbalanced to include match and mismatch pairs for each axis of rotation and question order was randomized. A sample item is presented in Figure 2.

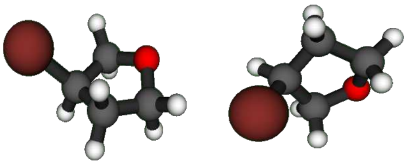


Figure 2. Sample test item. This represents a mismatch pair.

Embodied molecular visualization. We designed an embodied molecular visualization to allow learners to explore perspective-taking in organic chemistry. The computer visualization uses a novel human computer interaction (HCI) mode to allow students to physically align their perspective to see a virtual molecule from various vantage points. The visualization is a Java-based application that uses computer vision (OpenCV) face tracking algorithms to translate the location of a user's face in their physical environment into a virtual position within a 3D molecular environment. To do this, the application uses various mathematical transformations that take the position of the learners' face and infer where they would be positioned equivalently in the 3D scene. The location of the scene camera is then updated dynamically to establish this correspondence between the physical perspective-taking action and the computer visualization. A diagram depicting the HCI is shown in Figure 3.

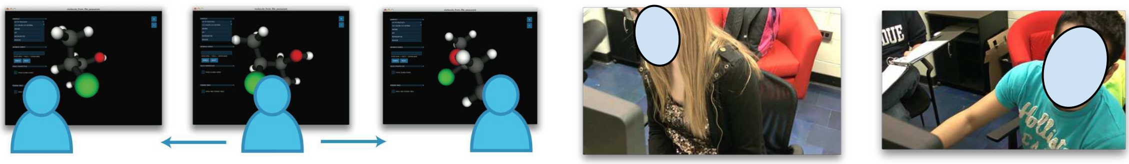


Figure 3. Depiction of human-computer interaction afforded by the embodied interface. Participants are depicted acting out perspective shifts to the right and left, respectively.

The embodied molecular visualization can load any organic molecule using both common (e.g., acetone) and systematic (e.g., propan-2-one) names and learners can take physical perspectives to explore transformations of the structure. This design, thus, directly reproduces the perspective-taking action presented in Figure 1 by allowing the user to assume the desired perspective when interacting with a rich 3D-visualization environment.

Instructional molecule transformation activity. Transformation was instructed in three sequential blocks corresponding to three spatial axes (*x*-, *y*-, and an axis in the *xy*-plane). Each block began with a short instructional video and was followed by interactive exploration trials. Instructional videos were short (~30 sec.), narrated clips showing a split screen with a "static reference molecule" (left) and a "transforming molecule" (right). The narrator explained, on reversing the transformation, how to determine whether the structures matched or not. Following the video clip, interactive exploration trials asked students to compare four molecule pairs (2 match, 2 mismatch) per axis, for a total of 12 trials. Interactive exploration trials used a split screen view identical to the instructional video. In the "embodiment" condition, students first saw an avatar demonstrate how to use the embodied molecular visualization to enact the desired transformation during the trial. Participants used the interface to take perspectives around a molecule corresponding to the current spatial axis and determined if the molecules were a match or mismatch. Students in the "no embodiment" condition were asked to make the same similarity judgements, where the transforming molecule was rendered using pre-recorded video clips of the molecule undergoing the spatial transformation. Students were directed to scrub through the clip with the computer mouse to make their similarity judgement. Students responded to a formative assessment prompt on each trial asking whether the molecules matched or not. A feedback page identified the response as correct or incorrect.

Survey of Self-reported Strategies. A 9-item survey was included to assess participants' perspective-taking strategies. Two of the questions asked participants to self-report their perceptions of confidence in their understanding of spatial transformation in chemistry on a 5-point Likert scale. One free response prompt was included that asked students to explain their process for solving spatial transformation assessment items, whether their process changed as a result of the intervention, and how specifically that process changed. Another 5-point Likert question asked participants to self-report their confidence in mentally imagining objects.

Procedure

Participants were randomly assigned to condition (embodiment, no embodiment) and seated at a computer workstation running a Qualtrics survey of the experimental protocol. The protocol contained five segments: (1) collect demographic data (e.g., GPA), (2) collect spatial ability scores, (3) pretest, (4) learning intervention, and (5) posttest. Both embodiment and no embodiment groups watched instructional videos introducing transformation and how pairs of organic molecules can be compared around a spatial axis. The embodiment group used the embodied visualization to complete the transformation activity; the no embodiment participants watched pre-rendered video clips of molecules transforming with respect to the relevant axis that they could scrub through with the computer mouse. All molecules were initialized to the same vantage point between conditions. Participants then filled out the post-intervention survey. Participants were offered either 1% extra credit in their chemistry course or $20 compensation for their time. This procedure was conducted with human subjects research approval.

Analysis

Each item on the spatial ability instrument had a total of two possible correct responses, each receiving one point, yielding a maximum total of 24 points. Items where the student provided more than two responses received zero points. Spatial thinking assessment items were scored using a binary scheme (0 = incorrect, 1 = correct). Items that received no response remained blank in the database. A maximum score of 16 was possible. Scores were converted to relative proportion correct.

Results

Prior to answering the hypothesis, we first analyzed whether there were randomly occurring group differences on independent measures of students' academic achievement and spatial ability. We used a one-way ANOVA to determine whether GPA or spatial ability differed by condition. Analyses revealed no main effect of condition for GPA, $F(1,102) = 0.005$, $p = 0.942$, nor of spatial ability, $F(1,100) = 0.941$, $p = 0.334$; thus, these covariates were not included in further analysis.

To what extent does an embodied software visualization controlled via bodily actions promote understanding of perspective-taking?

To answer the question of whether an embodied visualization supported student understanding of perspective-taking, we performed a repeated measures (pretest, posttest) ANOVA to compare achievement as a function of embodied instruction (embodiment vs. no embodiment). The analysis of between-subjects effects revealed that there was no main effect of condition, $F(1,102) = 0.124$, $p = 0.725$. Within-subjects comparisons indicated that there was no main effect of the repeated measure, $F(1,102) = 0.086$, $p = 0.770$, and no interaction of condition with pre/posttest scores, $F(1,102) = 0.563$, $p = 0.455$. Means and standard errors are presented in Figure 4.

We predicted that the use of the embodied visualization should provide learners with direct bodily experience of the abstract concept transformation and, as such, support them in better simulating transformation on the spatial thinking posttest. However, this analysis does not provide evidence to support the predictions of this study. Rather, the findings suggest that participants did not observe a selective benefit of embodiment. The lack of a statistically significant interaction indicates that students performed, on average, no differently from pretest to posttest by condition. Unexpectedly, the results indicate no improvement on transformation items from pre- to posttest.

The failure to observe differences on measures of spatial thinking between the conditions given the literature suggesting benefits of embodied instruction warrants further scrutiny. One possible explanation for this pattern of results is that students may have adopted alternative strategies to solving transformation items that bypassed engaging simulation. To determine whether participants adhered to the instruction and engaged in mentally simulated perspective-taking or whether they adopted unanticipated strategies, a post hoc analysis was performed on their responses to the post study survey to identify common solution processes used on transformation items.

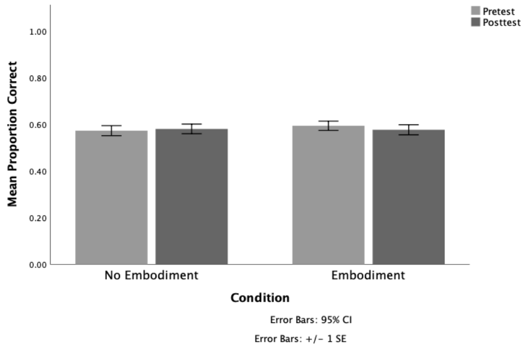


Figure 4. Plot of pre-/posttest proportion correct as a function of condition on the transformation subscale

What strategies do students report using to solve transformation items?

Responses to the post intervention survey were coded for strategies on solving spatial thinking items. Instances where students indicated strategies like using simulated mental spatial operations, e.g. rotation or perspective-taking, in addition to other analytic approaches, e.g. inspecting the constitution of the molecules to determine similarity, were coded and tallied. Strategy codes were not mutually exclusive, and students could self-report multiple strategies when solving spatial thinking items. Approximately 11.9% of responses could not be coded due to unclear language around solution process. Codes were assigned using a binary scheme (absent = 0, present = 1).

Strategies fell into four primary categories: rotation (76.9%), perspective-taking (9.6%), piecemeal transformation (5.8%), and inspecting internal features (23.1%). *Rotation* codes were applied to explanations where the student indicated that they imagined holistic movement of the molecule around an axis of rotation. *Perspective* codes were assigned when a participant's explanation indicated that they would imagine themselves moving about a molecule from an egocentric frame of reference. *Piecemeal* codes, by contrast, applied when the student indicated that they would individually rotate specific atoms or bonds around an axis of rotation. Finally, a strategy was tagged as *internal features* when the student indicated that they focused primarily on the constitution of the molecule, what atoms were present in both structures, and whether those atoms differed between the source and target molecules. Table 1 includes the coded strategies and examples of student responses to which each code was applied.

Table 1: Strategies reported by students on the post intervention survey

Strategy	**Proportion** (No Emb./Emb.)	**Example**
Rotation	76.9% (65.4% / 88.5%)	"I solved them by in my mind by rotation them…"
Piecemeal	5.8% (3.8% / 7.8%)	"When looking at the given model I would rotate the colored atom to where the other is and see if the form of the atom matched when moved around"
Perspective	9.6% (0% / 19.2%)	"I tried to look at them from different angles and see [whether] they could be a match or not."
Internal features	23.1% (15.4 % / 30.8%)	"I spent a little bit more time paying attention to every detail of the molecule, not just the position of the colors"

The results revealed, contrary to expectations, that the use of *perspective-taking* was explicitly invoked in self-reports of solution strategy in only a small minority of instances (9.6%). Of note, the instances of perspective-taking came solely from participants in the embodiment condition, but the absolute count was low (5 participants). Rather, the predominant strategy we identified was *rotation* (holistic & piecemeal) of the molecule around an axis of rotation. We also found that students frequently used analytic strategies like inspecting the specific *internal features* and molecular constitution to determine whether the molecules were a match pair without any clear indication that the student attempted to mentally transform their vantage point relative to the molecule or rotate the molecule itself.

This post hoc analysis indicates that students conceive of the task of transforming molecules around an axis as synonymous with that object *rotating* around the axis. This is in contrast to the spatially equivalent process of assuming multiple vantage points with respect to that molecule, and indeed, the specific spatial thinking strategy targeted by the embodied molecular visualization. That the use of the embodied molecular visualization did not induce a bias in students use of perspective-taking as a strategy to solve transformation items was unexpected and adds nuance to what simulations learners bring online when engaged in a spatial thinking task.

Discussion

In this study, we attempted to expand the design of embodied learning environments to teach students perspective-taking in the context of organic chemistry. We did this with an embodied software interface that coupled students' gestural activity (shifting physical perspective) to a responsive computer visualization. This design enabled participants to physically enact spatial transformations relative to specific fixed spatial axes. By linking learners' embodied actions to an interface, we predicted that this should afford simulable experiences rooted in body-spatial concept correspondence. We predicted this would, in turn, lead to learners attaining a more robust understanding of transformation. Therefore, the research questions we sought to answer with this study was: To what extent does an embodied software visualization controlled via bodily actions promote understanding of spatial concepts? What strategies do students report using to solve transformation items?

To achieve this aim, students' achievement on a spatial thinking assessment was compared using a mixed-design. The results of this study failed to find a statistical difference between the embodiment and no embodiment conditions. This pattern of results suggests that there was no clear evidence that embodied actions improved student understanding of transformation. The statistical comparison also did not provide evidence of any improvement at posttest irrespective of condition. To address alternative explanations of these results, a post hoc analysis of participants' self-reported solution strategies documented the problem solving processes students engaged. This analysis indicated that a majority of learners are broadly solving transformation items using mental simulation (76.9%), including mental rotation of the complete molecule, piecemeal rotation of individual atoms or substituents, and perspective-taking. This suggests that the embodied design did not give rise to a significant shift in students' approach to solving the problem as they primarily reported using mental rotation across conditions.

Another possible alternative explanation may be limitations of the assessment instrument itself, namely that the transformation items we selected were too difficult. While this possibility cannot be ruled out in the present study, the design of the stimuli was directly informed by other work with mental rotation paradigms using molecule stimuli. Indeed, prior work has already established that the mental rotation paradigm using molecule stimuli is tractable by this population. Stieff, Lira, & DeSutter (2014) demonstrated that students in the first five weeks of organic chemistry achieve 80% accuracy on match/mismatch judgements for planar (z-axis) rotations. Furthermore, Stieff, Origenes, DeSutter et al. (2018) have also demonstrated that this population can perform out of plane rotations (x-axis, y-axis) above chance.

These results are surprising in light of the hypothesized benefits that motoric action aligned to a responsive visualization should provide in learning via embodied actions. There are a few studies that have explicitly tested whether coupling bodily action to a responsive computer visualization provides benefits over an appropriate control. In a study of students learning about the trajectory of meteors under gravitational force, Lindgren, Tscholl, & Wang (2016) compared whether students who physically acted out the trajectories in an immersive room-sized simulation outperformed students who performed an analogous operation on a desktop computer. Lindgren et al. compared means on a posttest (using a subset of force concept inventory (FCI) items) and found that students in the immersive environment performed slightly better (0.6 items, Cohen's $d = 0.42$) than a control who used a computer to run the same simulation. However, the relatively low scores on this instrument (treatment: $M = 3.67$, $SD = 1.60$; control: $M = 3.00$, $SD = 1.58$) are close to chance for a 12-item multiple choice test with four response choices per item. Unfortunately, this study did not include a pretest measure and it is not possible to know whether students in the two groups began from the same baseline understanding of gravity.

Similarly, in a study of students' embodied understanding of centripetal force, Johnson-Glenberg and colleagues (2016) used a 2 x 3 mixed-design where they manipulated the simulation platform (full immersive room sized simulation (SMALLab), an interactive whiteboard, computer) and the fidelity of the embodied action to the concept (low, high). The simulation platform varied the immersiveness of students' acting out centripetal force by either swinging a projectile (SMALLab), using a pen on the interactive whiteboard, or by using a computer mouse. The authors varied the fidelity of embodiment to change the degree to which learners' embodied actions aligned to the concept centripetal force (i.e., high: using a pen at the interactive whiteboard to manipulate a virtual bob; low: controlling a slider that manipulated a virtual bob). The authors found no main effects of platform or degree of embodiment. What they did find was a difference on a delayed posttest: participants in the low embodied condition recalled less about centripetal motion on drawing prompts than students in high embodiment conditions.

Lindgren et al. (2016) and Johnson-Glenberg et al.'s (2016) findings are consistent with the findings from this study that embodied learning environments are not reliably yielding unambiguous positive effects on immediate posttests of content assessments. Johnson-Glenberg et al. detected a difference at delayed posttest, though, that suggests perhaps learning from embodied environments may only become clear when assessed over a delayed period of time compared to more traditional learning environments. However, the possibility of detecting differential learning using delayed posttest is unlikely to have helped in the present study given that no main effect of time was observed: students did not improve from pretest to immediate posttest, so we would not be able to observe similar differential performance at delayed posttest. Rather, it may be the case that some concepts, like transformation, require longer than a single intervention to be integrated into useful mental representations. Post-hoc reports indicated here that participants are predisposed to engage mental rotation, even if unsuccessfully.

This hypothesis of a temporal extent of learning spatial concepts from embodied learning environments is supported by studies in spatial training of domain general tasks. The stimuli used on the spatial thinking instrument require no specific chemical prior knowledge to answer correctly like domain general mental rotation tasks using block shapes. There is significant evidence that spatial skills like mental rotation are malleable with training (Uttal, Meadow, Tipton et al., 2013), but a common feature of interventions that target improving spatial skills like mental rotation and spatial visualization is extensive exposure (e.g., a 1-1.5 hr. dose) over a prolonged period—often weeks—of practice (e.g., Sorby, 2009; Wright et al., 2008). The short timescale of the intervention in this study, like others involving embodied designs, may simply not suffice to measurably boost performance on such items.

In addition to the difficulty of training spatial skills, student self-reports of strategy point to another unexpected finding. Rather than solving transformation items through simulated perspective-taking, the majority of participants engaged simulated rotation. Students overwhelmingly indicated a mental rotation strategy (76.9%) over perspective-taking (9.6%). This indicates that students either already had a crystallized conception of transformation as synonymous with rotation or this was somehow reinforced by the particular design of the embodied molecular visualization/instructional materials. It is unlikely that students' prior chemistry instruction can explain this asymmetry, primarily because spatial thinking skills like mental rotation receive no explicit instructional time in the chemistry classroom. It is more plausible that student conceptions of transformation were already crystallized around object-based rotation and it became salient through the intervention.

Another potential alternative explanation is that the embodied molecular visualization did not capitalize on a relevant embodied action in support of teaching transformation. This is a possibility that is supported by the post-intervention survey. If perspective-taking were the ideal embodied action for supporting student understanding of transforming molecular structures, then it should have appeared more clearly in student strategy choices after the intervention. While a pre-/post-intervention measure of strategy choice would be more definitive in establishing whether there was a detectable shift in strategy choice, the low proportion of self-reports invoking the perspective-taking strategy indicate that such a shift would likely have been of low practical significance. Furthermore, the design of this learning environment was directly informed by how current curricular materials present transformation of molecule structures as a perspective-taking operation (see Figure 1). It remains possible that transformation may more readily be apprehended as an object-based operation and that current curricular conventions should be challenged. Future work could more narrowly explore the potential interaction spatial operations in the curriculum and companion embodied interventions. Nevertheless, we still want to emphasize that these results do not show unambiguous benefits for embodied learning environments that map a principled bodily action to an underlying spatial thinking operation. That there was not a clear bias in the use of a perspective-taking strategy, especially among the participants in the embodiment condition, draws into question whether this simple mapping of perceptuomotor experience to mental representation oversimplifies the role that either prior knowledge or unintentional consequences of learning environment designs plays in students' ultimate conceptions.

Taken together, the results of this study indicate that improving spatial thinking with embodied actions is complex and that students do not simply receive a boost to their knowledge of disciplinary content by engaging their bodies using a responsive computer visualization. This study points to possible explanatory factors, namely the timescale of learning spatial concepts may be longer than was afforded in the present study and the unanticipated influence of competing spatial conceptions like rotation. Future studies should more narrowly explore the relationship between timescales and embodiment as well as the ways that prior knowledge and task structure might affect (or subvert) intended learning outcomes. Furthermore, embodied designs need to be tested against comparable alternatives given fundamental uncertainty over whether embodied designs are effective at all, and when they appear to be, what the practical effect of these designs is relative to other learning environments.

References

Abrahamson, D., Andrade, A., Bakker, A., Nathan, M. J., Walkington, C., Lindgren, R. W., ... Lindwall, O. (2018). Moving forward: In search of synergy across diverse views on the role of physical movement in design for stem education. *Proceedings of International Conference of the Learning Sciences*, ICLS, 2(2018-June), 1243-1250.

Andrade, A., Danish, J.A., & Maltese, A., (2017). Why are you gesturing? Elicited gestures and learning gains in an embodied learning environment. Paper presented at the *American Educational Research Association* AERA 2017, San Antonio, TX.

Barsalou, L. W. (2008). Grounded Cognition. *Annual Review of Psychology*, *59*(1), 617–645.

DeSutter, D., & Stieff, M. (2017). Teaching students to think spatially through embodied actions: Design principles for learning environments in science, technology, engineering, and mathematics. Cognitive Research: Principles and Implications, 2(1), 22.

Howison, M., Trninic, D., Reinholz, D., & Abrahamson, D. (2011). The Mathematical Imagery Trainer: From embodied interaction to conceptual learning. In G. Fitzpatrick & C. Gutwin (Eds.), *Proceedings of the ACM CHI Conference on Human Factors in Computing Systems* (CHI 2011), Vancouver, May 7-12, 2011.

Johnson-Glenberg, M. C., Megowan-Romanowicz, C., Birchfield, D. A., & Savio-Ramos, C. (2016). Effects of embodied learning and digital platform on the retention of physics content: Centripetal force. *Frontiers in Psychology*, 7(November), 1819.

Lindgren, R., & Johnson-Glenberg, M. (2013). Emboldened by embodiment: Six precepts for research on embodied learning and mixed reality. *Educational Researcher*, *42*(8), 445–452.

Lindgren, R., Tscholl, M., Wang, S., & Johnson, E. (2016). Enhancing learning and engagement through embodied interaction within a mixed reality simulation. *Computers and Education*, *95*, 174–187.

Nathan, M. J., & Walkington, C. (2017). Grounded and embodied mathematical cognition: Promoting mathematical insight and proof using action and language. *Cognitive Research: Principles and Implications*, *2*(1), 9.

Peters, M., Laeng, B., Latham, K., Jackson, M., Zaiyouna, R., & Richardson, C. (1995). A Redrawn Vandenberg and Kuse Mental Rotations Test - Different Versions and Factors That Affect Performance. *Brain and Cognition*, *28*(1), 39–58.

Sorby, S. A. (2009). Educational Research in Developing 3-D Spatial Skills for Engineering Students. *International Journal of Science Education*, *31*(3), 459–480.

Stieff, M., Dixon, B. L., Ryu, M., Kumi, B. C., & Hegarty, M. (2014). Strategy training eliminates sex differences in spatial problem solving in a STEM domain. *Journal of Educational Psychology*, *106*(2)

Stieff, M., Lira, M., & DeSutter, D. (2014). Representational competence and spatial thinking in STEM. *Proceedings of International Conference of the Learning Sciences, ICLS* , *2*(January), 987–991.

Stieff, M., Origenes, A., DeSutter, D., Lira, M., Banevicius, L., Tabang, D., & Cabel, G. (2018). Operational constraints on the mental rotation of STEM representations. *Journal of Educational Psychology*, *110*(8), 1160–1174.

Uttal, D. H., Meadow, N. G., Tipton, E., Hand, L. L., Alden, A. R., Warren, C., & Newcombe, N. S. (2013). The malleability of spatial skills: A meta-analysis of training studies. *Psychological Bulletin*, *139*(2), 352–402.

Wilson, M. (2002). Six views of embodied cognition. *Psychonomic Bulletin & Review*, *9*(4), 625–636.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review*, *15*(4), 763–771.

Zohar, A. R., & Levy, S. T. (2018). “Should I answer what the atom feels?” Learning about forces in chemical bonding using ELI-chem simulation. In *IDC 2018 - Proceedings of the 2018 ACM Conference on Interaction Design and Children* (pp. 650–656). New York, New York, USA: ACM Press.

Acknowledgements

Special thanks to Andrea Origines for her help collecting the data for this project. We would also like to thank Anna Szuba and Stephanie Werner for their feedback on a draft of this paper.