Collaboration Scripts Should Focus on Shared Models, Not on Drawings, to Help Students Translate Between Representations

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Abstract: Students often struggle to translate between physical and virtual models when learning concepts in STEM courses. Collaborative activities may help students overcome these difficulties, especially if collaboration scripts prompt students to discuss shared representations. Which representation should collaboration scripts focus students' interactions on? We investigate this question in a quasi-experiment with 560 undergraduate chemistry students. All students collaboratively built physical ball-and-stick models of molecules and translated them into wedge-dash drawings. Two experimental conditions received a collaboration script. For the *model condition*, the script prompted students to focus on the physical ball-and-stick models. For the *draw condition*, the script prompted students to generate intermediary drawings on paper. Compared to a *control condition* with unscripted collaboration, the *model condition* showed higher learning gains and the *draw condition* showed lower learning gains—especially for students with low spatial skills. Our results yield theoretical and practical implications for collaborative practices with multiple representations.

Keywords: Multiple representations, collaboration scripts, physical and virtual models, chemistry, spatial skills

Introduction

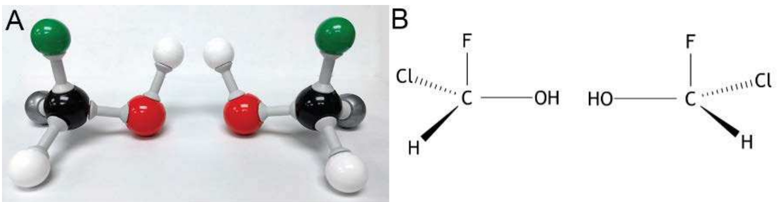

Figure 1. Physical ball-and-stick model (A) and wedge-dash structure (B). Each shows two isomers: molecules with the same molecular formula but different 3D arrangement of the atoms.

Figure 2. Students collaboratively work with physical ball-and-stick models and virtual wedge-dash structures.

Students in science, technology, engineering, and mathematics (STEM) often use multiple visual representations to illustrate abstract concepts (Ainsworth, 2008). For example, when learning about molecular geometry, students are typically asked to translate 3D physical ball-and-stick models (Figure 1A) into 2D wedge-dash structures (Figure 1B). To make these translations, they may work collaboratively with physical models and virtual representations (Figure 2). However, prior research shows that students often fail to spontaneously engage in effective collaboration strategies (Lou, Abrami, & D'Apollonia, 2001). Instructional support can alleviate these difficulties, for instance by providing collaboration scripts that prompt students to discuss how to translate between the representations. In our prior research, we found that such a collaboration script enhanced students' learning compared to unscripted collaboration during the same activity (Rau, Bowman, & Moore, 2017).

Collaboration scripts for translating between multiple representations may be effective because they focus students' collaborative interactions on shared representations. In our prior research, we observed two practices that are commonly promoted by instructors when students collaboratively translate physical into virtual representations. First, instructors often prompted students to focus on physical models they collaboratively constructed and to compare models directly to the virtual representation. Second, instructors often asked students to translate the physical representation into an intermediate drawing and compare the drawing to the virtual representation. Which of these instructional practices should collaboration scripts promote? We address this question in a quasi-experiment in which undergraduate chemistry students collaboratively translated physical ball-and-stick models into virtual wedge-dash structures to make sense of chemistry concepts related to molecular geometry.

Prior research

In the following, we briefly review research on students' difficulties in translating among multiple representations and collaborating effectively. We then discuss how collaboration scripts may alleviate students' difficulties by fostering the disciplinary practices of physical modeling and drawing.

Students' difficulties in translating between multiple visual representations

Many STEM concepts are visuospatial and/or not directly observable. To make these concepts accessible, instruction in STEM domains uses multiple visual representations (Ainsworth, 2008; Rau, 2017). For example, chemistry instruction typically uses physical ball-and-stick models with wedge-dash structures (Figure 1) to illustrate concepts related to molecular geometry. Students benefit from multiple visual representations only if they can translate between representations to make sense of the underlying concepts (Rau, 2017). However, many students struggle with such translations (Ainsworth, 2008), which can impede their success in STEM domains, including chemistry (Stieff, 2007).

Translating between representations is particularly difficult for students with low spatial skills (Stieff, 2007) because translating requires students to map the visual features of one representation to corresponding features in the other representation (Rau, 2016). To do so, students must hold visual features in working memory and mentally rotate the features to align them (Hegarty & Waller, 2005). By definition, students with lower spatial skills experience higher cognitive load during this task, which can jeopardize their learning from multiple visual representations (Hegarty & Waller, 2005; Stieff, 2007). Indeed, the chemistry education literature documents that students with low spatial skills have more difficulties in translating between representations, which can result in lower learning gains (Stieff, 2007).

Students' difficulties in collaborating with multiple visual representations

Collaboration can help students overcome difficulties in translating between representations because students can help each other map visual features and make sense of how representations show key concepts (van Dijk, Gijlers, & Weinberger, 2014). When working individually, students often fail to spontaneously reflect on their understanding of visual representations (Ainsworth, Bibby, & Wood, 2002). When working collaboratively, students may realize that they hold divergent views on the visual representations, which may prompt them to engage more deeply in making sense of the visual representations (Zhang & Linn, 2011). Further, collaboration may help students with low spatial skills receive support from peers to help them align and map features of different representations.

Yet, students often have difficulties in collaborating effectively (Lou et al., 2001; Weinberger, Stegmann, Fischer, & Mandl, 2007). Instructional support can help students overcome these difficulties, for instance by scripting their collaborative interactions. Such *collaboration scripts* can guide students' interactions, for instance, by asking questions for students to discuss or by prompting them to explain concepts to one another (Fischer, Kollar, Stegmann, & Wecker, 2013; Weinberger et al., 2007). In a prior experiment (Rau et al., 2017), we tested the effectiveness of a collaboration script that adaptively provided prompts to discuss representations when students reached an impasse in translating between representations. Results showed higher learning gains for students who received the collaboration script than for students who worked on the same activities without the script.

Supporting collaborative practices with multiple visual representations

Yet, prior research on collaboration scripts has not examined how to focus students' collaborative interactions on specific practices related to translating between multiple visual representations. Specifically, we observed two disciplinary practices that are common in classroom activities with multiple visual representations (NRC, 2012). Both of these practices serve to focus students' attention on a shared representation.

First, instructors often prompt students to focus on shared physical models. Prior research suggests that interactions with physical models can help students learn domain knowledge (Stull, Hegarty, Dixon, & Stieff, 2012). For instance, students' interactions with ball-and-stick models are constrained because the balls (atoms) have a designated number of holes for sticks (bonds), which are spread out as far apart as possible in a tetrahedral shape. Engaging in such interactions with the physical model can help students learn and retain information about the representation, such as how it shows molecular geometry and how to rotate the model for projection onto a 2D plane. Further, the ability to rotate physical models may also alleviate difficulties in mental rotation for students with low spatial skills (Barrett, Stull, Hsu, & Hegarty, 2014). However, much research suggests that models could hinder learning because students often do not know how to spatially align physical models with other representations to map features (Barrett et al., 2014). Because spatial alignment is particularly challenging for students with low spatial skills, focusing collaborative interactions on physical models could disadvantage students with low spatial skills.

Second, instructors often prompt students to draw additional visual representations on paper because it engages students in a valued disciplinary practice for STEM professionals (NRC, 2012). Professionals often draw intermediary representations to help them translate across representations during collaborations (Kozma & Russell, 2005). Prior research shows that drawing visual representations can help students learn domain knowledge (Schmeck, Mayer, Opfermann, Pfeiffer, & Leutner, 2014; Zhang & Linn, 2011). Further, drawing activities may facilitate mental rotation because students can physically orient their drawings on paper to map visual features. Indeed, prior research shows that spatial skills do not affect students' benefit from drawing activities (Schmeck et al., 2014). However, drawing activities without instructional support have been shown to result in high cognitive load, especially if the drawing task involves mental rotation (Schwamborn, Thillmann, Opfermann, & Leutner, 2011). This effect could disproportionally affect students with low spatial skills. Therefore, focusing students' collaborative interactions on drawing may disadvantage students with low spatial skills.

In our prior study on adaptive collaboration script for translating between representations (Rau et al., 2017), we observed both practices. First, students used a shared modeling kit to construct physical ball-and-stick models. Consequently, when the collaboration script prompted them to discuss translation between the representations, they often focused on the models. Second, our classroom observations showed that students often drew wedge-dash structures on paper when they reached an impasse, a practice encouraged by the teaching assistants in the course. Hence, either of these practices could have accounted for the effectiveness of our collaboration script. However, our prior experiment did not control for whether or not students were prompted to engage in either type of collaborative practice.

Research questions

Our brief review of collaborative practices in STEM shows that it is, to date, unclear whether prompting students to focus on physical models or to generate intermediary drawings will best support their learning with multiple visual representations. Based on Learning Sciences theory, one can argue both for potential positive and negative effects of each collaborative practice. Further, both collaborative practices are common in STEM professions and often encouraged by instructors in STEM courses. Therefore, our goal is to investigate:

Research question 1: Is a collaboration script more effective if it focuses students' collaborative interactions on physical models or on intermediary drawings in terms of enhancing students' learning of domain knowledge?

Further, because translating between representations is particularly difficult for students with low spatial skills (Hegarty & Waller, 2005; Stieff, 2007), we investigate:

Research question 2: Do students' spatial skills moderate the effects of model-focused and drawing-focused collaboration scripts?

Method

Chemistry course and participants

To address these questions, we conducted a quasi-experiment with 560 students in an undergraduate chemistry course at a Midwestern U.S. university. The course involved two 50-minute lectures attended by all students, one 50-minute discussion session, and one 3-hour lab session each week. Lab and discussion sessions were held in smaller sections of about 18 students each. The lab and discussion sessions were led by teaching assistants (TAs). All TAs received the same training in leading these sessions at the beginning of the semester. During the semester, students worked in small groups of 2-3 students during discussion and lab sessions.

Our quasi-experiment took place in a lab session which covered a topic related to molecular geometry: chemical isomers. Isomers are molecules made of the same atoms but differ in the spatial arrangement of their atoms. Instruction on isomers crucially relies on connecting the representations shown in Figure 1 because differences in the atoms' spatial arrangements within molecules can have dramatic effects on the properties of chemical compounds. For example, if students fail to understand the difference between the left and right isomers in both Figure 1A and 1B, they may fail to understand that the melting point of the left isomer differs from the melting point of the right isomer.

Experimental design

The chemistry course had 34 lab sections. Two experimental conditions received a collaboration script. Specifically, five lab sections (n = 78 students) were assigned to the *model condition* that received a model-focused script. Six lab sections (n = 110 students) were assigned to the *draw condition* that received a drawing-focused script. The remaining 23 sections were assigned to a *control condition* (n = 383 students) that received no collaboration script. Students selected lab sections at the beginning of the semester to fit their schedule. We do not have any reason to believe that systematic differences exist between sections.

During the lab sections, all students worked collaboratively in dyads with the visual representations shown in Figure 1 on a sequence of chemistry problems. The problems required students to construct a physical ball-and-stick model of a specific isomer and to translate it into a wedge-dash structure. Further, each problem contained conceptual questions that required students to use the representations to make sense of concepts related to isomers.

Experimental conditions

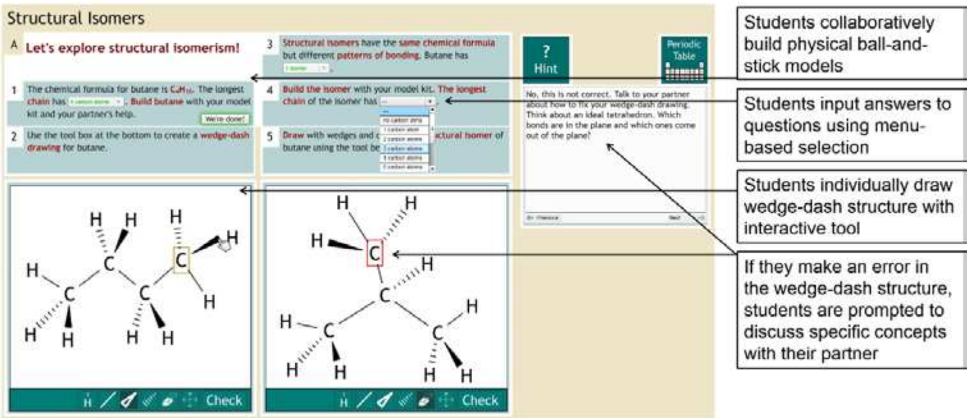

Figure 3. Students draw virtual wedge-dash structures of structural isomers in Chem Tutor.

The model and draw conditions received a collaboration script that prompted them to discuss how to translate between physical ball-and-stick models and virtual wedge-dash structures while they solved chemistry problems. As in our prior study (Rau et al., 2017), the collaboration script was implemented in an educational technology that presented the chemistry problems: Chem Tutor (see Figure 3). The Chem Tutor problems were created to be identical (i.e., same steps, same questions, same molecules) to problems on a paper worksheet traditionally used in this lab session. Chem Tutor instructed students to build the model collaboratively, input answers using a drop-down menu, and draw the wedge-dash structure in an interactive tool. If students made an error on a problem, the collaboration script provided immediate feedback by highlighting the part of the conceptual question or of the wedge-dash structure that was incorrect and prompting students to discuss it with their partners (Figure 3). Throughout all lab sessions for the model and draw conditions, the first author and several research assistants provided technical support with Chem Tutor. The TA for each session answered questions about the content, as they typically do for each lab session.

The difference between the model and the draw conditions regarded the introductory prompts in the collaboration script and an equivalent spoken prompt provided at the beginning of the lab session. Students in the *model condition* received prompts to "carefully build and orient their physical ball-and-stick models" before constructing virtual wedge-dash structures in Chem Tutor. Students in the *draw condition* received prompts to "plan their wedge-dash structures on paper" before constructing them in Chem Tutor. The respective prompts state that the practice of "constructing models" or "drawing on paper" benefits students because it "aligns with the work of professional chemists and is an essential part of their reasoning process."

Control condition

A "business-as-usual" control condition did not receive a collaboration script. Students solved the same sequence of chemistry problems using a paper worksheet traditionally used in this lab session. The worksheet contained the same problem-solving steps, conceptual questions, and isomers. Students also used a shared modeling kit to construct the physical ball-and-stick models, but they wrote down answers to the conceptual questions and drew wedge-dash structures on the worksheet without a collaboration script. At the end of the 3-hour lab session, TAs collected the worksheets to provide written feedback on problem solutions and wedge-dash drawings in the following week's lab session.

Assessments

To assess students' learning of domain knowledge, we used a *pretest* and *posttest* on isomers, evaluated in our prior study (Rau et al., 2017). A *retention scale* of the test assessed students' ability to recall isomer concepts from the lab. A *transfer scale* assessed students' ability to apply this knowledge to predict the stability of molecules.

To assess students' *spatial skills*, we used the Vandenberg & Kuse test for mental rotation ability (Peters et al., 1995). This test was evaluated and used in prior research on chemistry learning (e.g., Stieff, 2007).

Procedure

We conducted our study as part of an undergraduate chemistry course. A lecture in week 3 of the semester covered molecular geometry and chemical isomerism. In week 4, students worked on activities in accordance with their typical lab schedule. First, as the required pre-lab exercise, students completed the pretest and spatial test online. Then, during their scheduled 3-hour lab session, students completed problems using Chem Tutor or worksheet that corresponds to their condition. Lastly, students completed the posttest online as the required post-lab exercise at the end of week 4.

Results

Prior checks

Table 1: Means and standard deviations (in parentheses) of test scores by condition

		Retention scale		Transfer scale	
Condition	**Spatial test**	**Pretest**	**Posttest**	**Pretest**	**Posttest**
Control	.881 (.140)	.527 (.190)	.651 (.195)	.540 (.403)	.745 (.356)
Model	.875 (.132)	.515 (.170)	.630 (.202)	.654 (.397)	.801 (.326)
Draw	.857 (.166)	.541 (.186)	.628 (.210)	.727 (.369)	.764 (.375)

Because we used a quasi-experimental design in which students were not assigned to conditions at random but based on their lab section, we first checked for potential differences between conditions prior to the intervention. Table 1 shows the means and standard deviations of test scores by condition. A multivariate analysis of variance (MANOVA) with condition as independent factor and test scores (retention pretest, transfer pretest, and spatial skills test) as dependent measures showed no significant differences between conditions on the retention pretest ($F < 1$) or on the spatial skills test, $F(2, 570) = 1.24$, $p = .291$. However, there was a significant difference on the transfer pretest, $F(2, 570) = 10.61$, $p < .01$. Post-hoc comparisons showed that students in the draw condition had significantly higher scores than students in the control condition ($p < .01$). No other differences were significant at the pretest. To account for pretest differences, all following analyses use pretest scores as a covariate. Next, we checked for learning gains from pretest to posttest. A repeated-measures ANOVA showed significant learning gains on the retention test, $F(1, 570) = 145.63$, $p < .01$, as well as on the transfer test, $F(1, 570) = 75.37$, $p < .01$.

Differences between conditions

Because we conducted a quasi-experiment with assignment to condition by lab section rather than by student, we used a hierarchical linear model (HLM) to analyze differences between conditions. HLMs take into account nested sources of variance due to the fact that, for instance, students taught by the same teaching assistants tend to have more similar knowledge than students taught by different TAs. Specifically, we used an HLM that included a random intercept for TAs. In addition, the HLM included pretest scores as a covariate to control for pretest differences prior to the intervention, condition as independent factor to test research question 1, and spatial skills and an interaction effect of condition with spatial skills to test research question 2.

On the retention posttest, there was no significant main effect of condition ($F < 1$) nor a significant interaction between condition and spatial skills ($F < 1$). On the transfer posttest, there was a significant main effect of condition on learning gains, $F(2, 564) = 5.03$, $p < .01$, such that the model condition outperformed the control condition and the control condition outperformed the draw condition. This effect was qualified by a significant interaction between condition and spatial skills, $F(1, 564) = 4.75$, $p < .01$. To gain insights into the nature of this interaction effect, we split students into groups with low spatial skills (0-33rd percentile on the spatial skills test), medium spatial skills (34th-66th percentile), and high spatial skills (67th-100th percentile). Post-hoc comparisons showed that the effect of condition was significant only among students with low spatial skills ($p < .05$), but not among students with medium or high spatial skills ($ps > .10$). Figure 4 illustrates these effects.

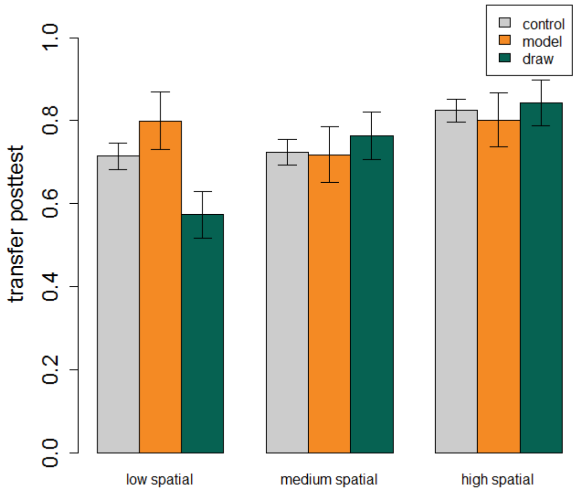

Figure 4. Average scores on transfer posttest by condition and post-hoc splits into low (0-33rd percentile), medium (34th-66th percentile), and high (67th-100th percentile) spatial skills. Error bars show standard errors of the mean.

Discussion

This study investigated the effects of two disciplinary practices on a collaboration script that supports translation between multiple visual representations. Specifically, we tested whether a collaboration script is more effective if it focuses students' collaborative interactions on physical models or on generating intermediary drawings (research question 1). We found no effects on retention of chemistry knowledge. This finding is not surprising because collaborative interactions are known to be less effective for the acquisition of simple knowledge than for complex knowledge (Kirschner, Paas, & Kirschner, 2010). Accordingly, we found higher learning gains on a test of chemistry knowledge transfer for students who received a model-focused collaboration script, compared to unscripted collaboration in a control condition. By contrast, students who received a drawing-focused collaboration script showed lower learning gains on the transfer test than the control condition.

In addition, because translating between representations is particularly difficult for students with low spatial skills, we investigated whether students' spatial skills moderate the effects of model-focused and drawing-focused collaboration scripts (research question 2). We found that the advantage of the model-focused collaboration script and the disadvantage of the drawing-focused script were particularly pronounced for students with low spatial skills.

Why might the drawing-focused collaboration script have resulted in lower learning gains than unscripted collaboration? We propose three potential reasons. First, drawing intermediary representations might result in cognitive overload, particularly for students with low spatial skills. The purpose of the lab session in which we conducted our experiment was for students to learn to translate ball-and-stick models into wedge-dash structures. Hence, students were not yet proficient at generating drawings to translate between these representations. When asking students to draw on paper to plan their wedge-dash structures, students receive no support for doing so. Drawing without support can increase cognitive load (Schwamborn et al., 2011), especially for students with low spatial skills (Hegarty & Waller, 2005; Stieff, 2007), which in turn may impede learning. Second, focusing students' collaborative interactions on drawings may reduce translation and sense making between the target representations. In our lab session, the goal was to learn to translate physical ball-and-stick models into wedge-dash structures. Because students in the draw condition were asked to plan their wedge-dash structures on paper first, they may have focused on copying the wedge-dash structure from the paper rather than reflecting on how it translates from the ball-and-stick model. Third, focusing students on generating drawings may reduce collaboration altogether. Even though the collaboration script prompted students to discuss intermediary drawings with their partner, students drew individually on their own piece of paper, which implies ownership. Focusing students' collaborative interactions on representations that they "own" may discourage collaboration—for instance, a partner may be less inclined to modify someone else's drawing. This might, in turn, reduce reflection on how the representations show concepts (van Dijk et al., 2014).

Why was the model-focused collaboration script effective, in particular for students with low spatial skills? We consider two potential reasons. First, focusing students' attention on the ball-and-stick models may have increased collaboration. Students used a shared modeling kit to build the physical ball-and-stick models. Because students built models together, they "co-owned" the models, which may have encouraged them to modify the models while answering conceptual questions and constructing wedge-dash structures. Second, students with low spatial skills may particularly benefit from collaborative interactions that focus on physical models because their partner can help them spatially align the representations. To translate physical ball-and-stick models into wedge-dash structures, students have to mentally project the 3D model into a 2D plane for the wedge-dash structure. By definition, students with low spatial skills have more difficulties than students with high spatial skills in mentally rotating objects. Students in the model condition were prompted to collaborate with their partner to spatially align the physical ball-and-stick models with wedge-dash structures. The partners of students with low spatial skills may have helped them externally rotate the physical model to facilitate projection from 3D into 2D.

Limitations

Our results should be interpreted in light of the following limitations. First, causal inferences from quasi-experiments are generally limited because non-random differences between conditions may exist. Although we took all possible steps to ensure the equivalency of the conditions, an experiment with random assignment of individuals to conditions should replicate our results. Second, our experiment was situated in the context of a specific chemistry course. Even though we consider the naturalistic context of our experiment a strength in terms of external validity, future research should test if our results generalize to other STEM courses. Finally, our experiment focused on two specific representations. Therefore, future research should replicate our findings in other STEM domains that use different physical and virtual visual representations (e.g., 3D and 2D protein models in biology, geological layers and block diagrams).

Conclusion

Our results contribute to theory about collaborative learning. We provide novel insights into the mechanisms that may account for the effectiveness of collaborative activities on students' learning with multiple visual representations. We isolated two possible mechanisms that focus students' collaborative interactions on physical models or on generating intermediary drawings. Our findings suggest that, especially for students with low spatial skills, focusing shared attention on physical models is a mechanism through which collaboration may enhance students' learning, whereas focusing on intermediary drawings is a mechanism through which collaboration might hinder students' learning.

Further, our results make practical recommendations for the design of collaboration scripts and collaborative practices in STEM instruction. We recommend that collaboration scripts focus students' collaborative interactions on shared models rather than on intermediary drawings. Further, we caution instructors against encouraging students to generate intermediary drawings when translating between representations, especially if they have low spatial skills. Our study shows that even a simple tweak of how students are prompted to collaboratively use shared representations can render a collaboration script more or less effective than unscripted collaboration.

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