Title

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Timelines or time cycles:

Exposure to different spatial representations of time influences sketching and diagram preferences

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Abstract

Visual representations of information are prevalent in many academic domains, and students must learn how to interpret and use these visual representations. How do students acquire this representational competence? Past work has focused on the role of explicit instruction. In this work, we consider another route for acquiring representational competence in the domain of biology. We argue that students develop representational competence with diagrams based on experience with diagrams with specific features. In two studies (Study 1 $N = 161$, Study 2 $N = 195$), we presented undergraduates with a lesson on metamorphosis with either a linear or circular depiction of the ladybug life cycle, two common arrangements for this type of diagram. We then assessed students' life cycle drawings and their preferences for different features of life cycle diagrams. This brief exposure to diagrams with a particular feature led to changes in participants' self-constructed diagrams and in their preferences for the specific diagrammatic features to which they were exposed. Our studies suggest that people develop representational competence, at least in part, by tracking the features present in the visualizations they see in their environments.

Keywords: Experience, representational competence, diagrams, multimedia learning, spatial arrangement, biology education

Timelines or time cycles: Exposure to different spatial representations of time influences sketching and diagram preferences

Visualizations, such as diagrams, images, and other schematics, are prevalent in education and instructional materials. Visualizations are found in classrooms (Fisher et al., 2014), museums (Horn et al., 2016), textbooks (Menendez, Mathiaparanam, et al., 2020), educational technology systems (Nagashima et al., 2021), and tests (Lindner, 2020). Generally, studies have found that students learn better with lessons that include visualizations (also called multimedia lessons) than from lessons with text alone (Carney & Levin, 2001). However, using visualizations to teach concepts can also be problematic. Visualizations by design are symbolic and they involve formalisms that might not be obvious to students (Kozma & Russell, 1997; Novick, 2006). This means that, when first presented with a visualization during a lesson, students have to simultaneously make sense of a visual representation they have never seen and use that representation to aid their understanding of the material (Rau, 2017a). In this paper, we examine how experience with diagrams (i.e., seeing a diagram in a lesson) affects how students make sense of visual representations.

Prior work examining how students make sense of diagrams and other visualizations has focused on students' *representational competence* (diSessa & Sherin, 2000; Rau, 2017b). Representational competence is considered a key component of scientific literacy (Nitz et al., 2014) and has been proposed to comprise four skills: interpreting (the ability to make sense of representations), selecting (the ability to choose a representation that is appropriate for a problem or scenario), constructing (the ability to create a representations of a problem or scenario and translating (the ability to go from one representation to another; Kozma & Russell, 1997; Stieff & DeSutter, 2020). Although representational knowledge and content knowledge in a domain might appear to be related, several studies have shown that they are distinct and develop separately, with interventions aimed at improving student's representational competence yielding large changes in students' use of and reasoning with visualizations, but very small effects on content knowledge (Kohl & Finkelstein, 2006; Nitz et al., 2014; Stieff, 2011). Additionally, representational competence is thought to be discipline-specific, with competence with representations in one discipline not generalizing to representations in other disciplines (Cheng, 2018). Given the importance of representational competence in scientific literacy and science education, it is crucial to understand how students acquire this competence.

One manner in which students might develop representational competence is through explicit instruction. Analyses of classroom interactions suggest that although students sometimes link representations to the associated concepts correctly, this process can be facilitated by instructional scaffolding (Rau, 2017a). Studies have found that when teachers spend more time on topics related to representational competence, their students have better representational skills (Kohl & Finkelstein, 2006; Stieff, 2011). Instructional strategies such as asking students to draw visualizations and then revise those drawings also support the development of representational competence (Wu & Rau, 2018). This suggests that teachers can support the development of representational competence by explicitly teaching students how to interpret visualizations.

However, explicit instruction is not always required for students to use representations effectively. Rau (2017a) has shown that students are sometimes able to make connections between concepts and visualizations without the help of an instructor. Additionally, many studies that have shown benefits of including visualizations in lessons have not taught students how to make sense of these visualizations (Cooper et al., 2018; Lindner, 2020; Menendez, Rosengren, et al., 2020). This suggests that although understanding visualizations can be difficult, students can sometimes make sense of visualizations on their own and then use the visualizations to support their learning.

Students might be able to make sense of new visualizations by using their prior experience with other visualizations in the same discipline. As mentioned previously, visualizations can be found throughout educational materials, therefore, students might be able to use their previous experience with other visualizations to make sense of the features of novel visualizations. This alternative approach builds on the cognitive psychological literature on perceptual learning (Goldstone et al., 2010; Kellman et al., 2010), which is a form of learning in which experience changes people's perception, enabling more effective extraction of meaningful information from perceptual information (Gibson, 1963; Goldstone, 1998). Applied to visualizations, perceptual learning about visualizations with particular features should lead to better processing of visualizations with similar features. There is some correlational support for this idea. Menendez et al. (2022) showed that children learn more from a lesson that uses diagrams with features that are common in books targeted to their age group.

In the current research, we investigate whether experience with diagrams supports students' representational competence, as measured by students' preferences and drawings. We examine whether brief experience with a specific diagram leads students to prefer diagrams with similar features and to construct diagrams that have similar features.

Features of visualizations

Several studies have shown that the specific features of visualizations influence whether and to what extent students benefit from the presence of visualizations (Cooper et al., 2018; Mayer, 2008; Schnotz, 2014). These features include the spatial arrangement of information (Novick et al., 2011) and the realism of the depictions (Menendez et al., 2022). For example, Menendez et al. (2020) found that adults generalize more broadly after a lesson on metamorphosis if they saw a bland diagram (with no color and few details) than if they saw a rich diagram (with lots of color and detail). They suggest that students inferred that the lesson with the bland diagram applied to a broader category (e.g., insects), but that the lesson with the rich diagram applied more narrowly to the specific animal used in the lesson (e.g., the ladybug). These findings suggest that visualizations with certain features might lead students to make different inferences. The spatial arrangement of the diagrams can also influence performance (Novick et al., 2011). In the case of life cycle diagrams (i.e., diagrams depicting the different stages of an organism— the type of diagram used in the current studies), there are two predominant spatial arrangements: circular, in which the life stages of an organism are organized in a circle in order to create a cycle or clock, and linear, in which the life stages of an organism are organized in a line in order to create a timeline (Menendez, Mathiaparanam, et al., 2020). See Table 1 for examples of both types of arrangements.

Current Studies

In the current studies, we examined people's representational competence in the context of biology learning, specifically learning about metamorphosis. We focus on metamorphosis as it is a domain in which visualizations have been shown to enhance learning among children and adults (Menendez, Rosengren, et al., 2020; 2022). Additionally, unlike some content areas in which there are multiple kinds of visualizations that an instructor can use, lessons on metamorphosis typically use the same type of visualization, namely, life cycle diagrams. Content analyses of life cycle diagrams have shown that the most life cycle diagrams include simple or colorless backgrounds, most include rich and detailed depictions of each life stage, and most depict only one generation (Menendez, Mathiaparanam, et al., 2020). The spatial arrangement of the stages (either linear or circular) is the focus of the current studies. We focus on this feature because it is salient and it has been the focus of prior work (Tversky & Jamalian, 2021). The primary goal of this paper is to assess whether experience with particular diagrammatic features influences the choices that participants make when selecting and constructing visualizations.

We exposed participants to life cycle diagrams that were either linear or circular during a brief lesson about the life cycle of a butterfly. We assessed participants' representational competence by focusing on two skills: *selecting* and *constructing* representations. We assessed participants' selection skill through a diagram preference task, modelled after Bartel et al. (2021), in which participants were asked to *select* which of two diagrams best showed the life cycle of an organism. This task assesses selection skill because participants are given different representations and they have to choose the one that best aligns with the given prompt ("Which diagram best shows the life cycle of [animal]"). We assessed participants' construction skill through a drawing task, in which participants were asked to sketch the life cycle of an animal. This task assesses construction, as participants created a visualization that reflects their internal model of the life stages of a particular animal. In Study 1, participants completed the drawing task before and after the lesson, and they completed the diagram preference task after the lesson. In Study 2, participants completed both tasks before and after the lesson. We hypothesized that participants who saw a circular diagram during the lesson would be more likely than those who saw linear diagrams to draw circular diagrams after the lesson. Additionally, we expected that participants who saw a circular diagram during the lesson would be more likely than those who saw linear diagrams to select circular diagrams as the best depictions of the life cycle.

As a secondary goal, we also examined whether people make different inferences based on features of the diagrams, as suggested by Menendez et al. (2020). To assess this, we examined the correspondence between diagram richness and the category participants inferred was being represented by the exemplar in the diagram. We hypothesized that participants would infer that a bland life cycle diagram refers to a broader category more often than a rich life cycle diagram.

Study 1

Method

Participants

We recruited 163 undergraduate participants (91 women, 63 men, 1 non-binary, 8 who did not report gender) from an Introduction to Psychology course at a large research university in the midwestern United States. The racial/ethnic breakdown of the sample was 69.3% White (*n* = 113), 12.3% Asian or Asian American (*n* = 20), 3.1% Hispanic or Latinx (*n* = 5), 2.5% Black or African American (*n* = 4), 1.2% Native American (*n* = 2), and 4.9% mixed or bi-racial (*n* = 8); 6.7% did not respond (*n* = 11). Participants completed the study for extra credit.

Tasks

The study was administered through the online survey platform Qualtrics. In addition to the tasks described below, participants also completed two attention checks. All participants passed both checks. Participants also completed two questions that assessed their knowledge about the origins of species. As these questions are not relevant to the current study's aims, these questions will not be discussed further but can be found in the supplemental materials.

Drawing task. To allow people to draw the life cycle of animals in the online study format, we used the "signature" question type in Qualtrics, with the box size set to "small". We used the small box size because it was approximately a square, while all the other sizes are rectangular. The box shape might afford different spatial organization, and thus might influence the type of drawings people make. Participants were asked to draw the life cycle of a butterfly at pretest and the life cycle of a ladybug at posttest. After drawing the life cycle, we asked participants to write an explanation of the life cycle of the animal in a text box.

Life cycle knowledge task. We used a modified version of the task used in Menendez et al (2020) to assess participants' knowledge of life cycle changes. This task was used at both pretest and posttest. Detailed information on this task and how performance varied by condition is presented in the supplemental materials.

Lesson. We used a modified version of the video lesson used by Menendez et al. (2020) on the life cycle of the ladybug. The lesson was approximately 1 minute and 30 seconds long. The full text of the lesson can be found in the supplemental materials, and the lesson videos can be found at https://osf.io/b6qcg/?view_only=ee9da69cf2ea41b987ad1e0c653448f5. The lesson shows a static life cycle diagram that is visible for the duration of the entire lesson. Throughout the lesson, the different stages of the life cycle are highlighted with yellow circles. We created two versions of the video lesson, one with a circular life cycle diagram and one with a circular life cycle diagram (see Table 1). Both lessons were identical except for which diagram was presented. After the lesson, we asked participants to recall the label for each stage (i.e., egg, larva, pupa, adult).

	Circular	Linear

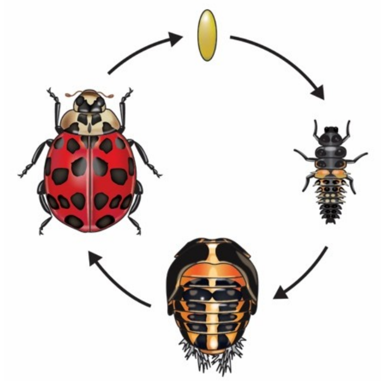
Lesson diagrams		
Participants' drawings		

Table 1. Linear and circular diagrams of the life cycle of a ladybug used in the lesson.

Demographics. We asked participants to report demographic characteristics, including their age, gender, race/ethnicity, major, and biology courses taken.

Diagram preference. We created a diagram preference task modelled after Bartel et al. (2021). We asked participants "Which of these two diagrams do you think better shows the life cycle of **a butterfly**?" or "Which of these two diagrams do you think better shows the life cycle of **butterflies**?" Question type was varied between subjects, but it did not influence participant responses, so we collapse across question type in the analyses presented in this paper. Under the question, participants saw two diagrams that were identical except for one feature, and they were asked to select one of the diagrams. Participants were asked about both animals and plants in 12 trials, with three of these being the key trials in which participants were asked to select between a linear diagram and a circular diagram. There were also 3 trials that tested preference for color or black-and-white, 2 trials that tested preference for labels or no labels, 2 trials that tested preference for open or closed circles, and 2 trials that tested preference for lines or open circles.

Label-richness preference. We also presented participants with two diagrams of the ladybug life cycle that varied in perceptual richness (used in Menendez et al., 2020; 2022). On one trial, we presented participants with the bland and rich life cycle diagrams and asked, "Which of these two diagrams do you think better shows the life cycle of **a ladybug**?" On another trial, we asked, "Which of these two diagrams do you think better shows the life cycle of **an insect**?" These questions were interspersed within the diagram preference task. Additionally, on one trial, we presented the rich diagram and asked, "What do you think is being depicted in this diagram?" Participants could select "the life cycle of a ladybug" or "the life cycle of an insect." Another trial asked the same question but showed the bland diagram. The order of these questions was counterbalanced. These questions examined whether people infer that diagrams of varying richness refer to different category levels (a mechanism proposed in prior research, Menendez et al., 2020; 2022).

Procedure

Participants first saw an information sheet that explained their voluntary participation in the study and checked a box indicating that they consented to participate in the study. They then completed the experimental tasks in the following order: (1) butterfly life cycle drawing and explanation, (2) life cycle pretest, (3) randomly-assigned lesson with either the linear or circular diagram, (4) life cycle posttest, (5) ladybug life cycle drawing and explanation, (6) origin-of-species questions, (7) demographic survey, and (8) diagram preference and label-richness preference tasks.

Drawing coding

Of the 324 drawings, 18 (5.5%) were not clear enough to code and were therefore discarded. We coded participants' drawings for a variety of features, such as the number of stages and arrows, whether they included an arrow connecting the first and last stage, and whether they depicted death. Critically, we coded whether the drawings depicted the different stages in a linear or circular arrangement. One coder coded all of the drawings and a second coder coded one-third of the drawings to assess reliability. Reliability for all codes was acceptable, and disagreements were resolved through discussion. Examples and descriptions of all codes, as well as prevalence rates and reliability estimates are provided in the supplemental materials. Reliability for the shape of the drawing was also acceptable ($\kappa = 0.83$).

Results

We first present analyses of participants' drawings. Then, we present analyses of participants' diagram preferences followed by their label-richness preferences. Because all dependent variables are binary outcomes (e.g., the participant drew a circle or not, selected the circular diagram or not), we used logistic regression to predict the probability that participants drew a circular diagram or selected a particular diagram. Because participants made multiple drawings or made multiple selections, we analyzed the data using mixed-effects models that model each drawing or selection as a separate trial. We report odds ratios (OR) as effect size estimates. Odds ratios show a multiplicative relation (e.g., if OR = 2, then it means that the odds of participants in one group drew a circle or not were twice as high as the odds in the other group). Therefore, for all analyses we used logistic linear mixed-effect models. We kept the random effect structure maximal, and if models failed to converge, we followed the recommendations of Brauer and Curtin (2018) to achieve convergence. We report the results and random effect structure of the first model that converged. All materials, data, and analysis scripts for both studies can be found at: https://osf.io/b6qcg/?view_only=ee9da69cf2ea41b987ad1e0c653448f5.

Life cycle knowledge task. We examined whether participants learned about metamorphosis after the lesson. Full details of the analysis can be found in the supplemental materials. Overall, we found participants endorsed metamorphosis more at posttest than pretest, but there was no significant difference in learning between the two diagram conditions. Thus, participants learned equally well from the lesson with the linear diagram and the lesson with the circular diagram.

Drawing task. We examined whether participants' life cycle drawings differed from pretest to posttest. We predicted the likelihood that participants drew a circular diagram from test time (coded -0.5 for pretest and 0.5 for posttest), diagram condition (coded -0.5 for linear and 0.5 for circular), and their interaction. The first model to converge included by-subject random intercepts and by-subject random slopes for test time, but did not allow them to correlate. We found a significant main effect of test time, $OR = 2.61$, Wald's χ^2 $(1, N = 158) = 5.39$, $p = .020$, a significant main effect of diagram condition, $OR = 10.49$, Wald's χ^2 $(1, N = 158) = 10.07$, $p = .001$, and a significant interaction, $OR = 149.06$, Wald's χ^2 $(1, N = 158) = 19.97$, $p < .001$. As can be seen in Figure 1, at pretest, participants were equally likely to draw a linear or a circular diagram (both bars around 50%). However, at posttest, participants who saw the circular diagram during the lesson were more likely to draw a circular diagram, and participants who saw the linear diagram during the lesson were less likely to draw a circular diagram (and hence more likely to draw a linear diagram).

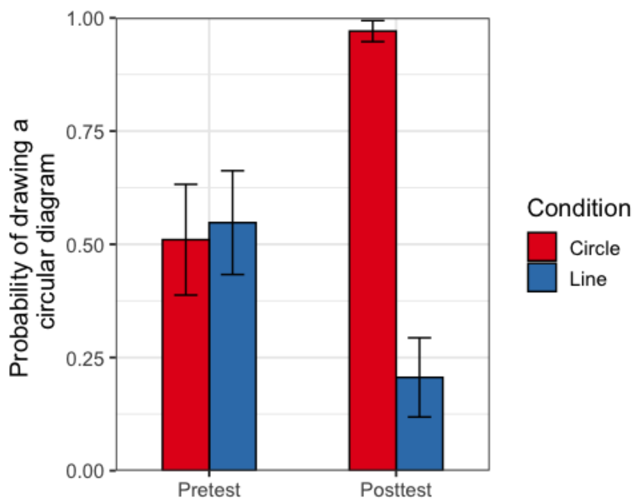


Figure 1. Probability of drawing a circular diagram at pretest and posttest by lesson diagram condition. Error bars show the within-subject standard errors of the point estimates.

Diagram preference. We examined participant's preferences for diagrams with different features. As can be seen in Table 2, participants overwhelmingly preferred diagrams with color and diagrams that included labels. They also preferred closed circles (rather than open circles), and lines rather than open circles. Critically, we examined whether participants' preference for linear versus circular diagrams depended on the diagram that they saw during the lesson. We predicted the likelihood that participants selected the circular diagram (rather than the linear one) on any given trial from diagram condition, and we included by-subject random intercepts. We found an effect of diagram condition, *OR* = 6.52, Wald's χ^2 (1, *N* = 161) = 14.65, $p < .001$, such that those who saw the circular diagram in the lesson preferred circular diagrams whereas those who saw the linear diagram in the lesson did not show a preference for either configuration. See Figure 2.

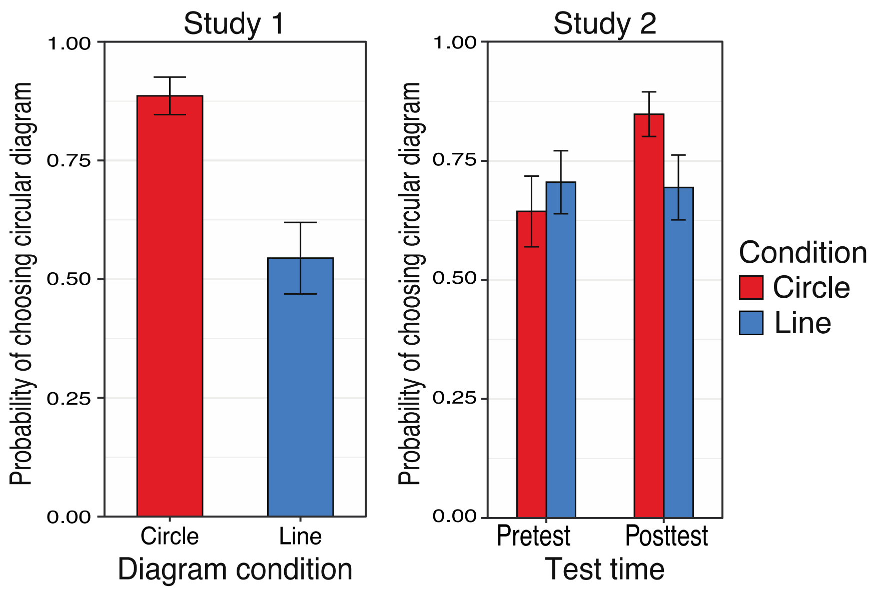


Figure 2. Model predictions of the probability of selecting a circular over a linear life cycle diagram in the diagram preference task, separated by the diagram participants saw during the lesson. The left panel shows the results for Study 1 and the left panel shows the results for Study 2. Error bars show the within-subject standard errors of the point estimates.

Table 2. Preference for different features of diagrams.

	Study 1		Study 2			
	Posttest		Pretest		Posttest	
Comparison	Linear	Circular	Linear	Circular	Linear	Circular
Color (over black-and-white)	94.6%	91.2%	94.5%	94.7%	91.1%	91.5%
Labels present (over absent)	97.5%	94.4%	95.9%	95.8%	98.5%	97.9%
Circle (over line)	53.0%	77.2%	62.1%	58.0%	61.2%	70.7%
Line (over open circle)	75.0%	66.9%	68.6%	74.5%	75.8%	72.2%
Closed circle	66.5%	75.3%	59.7%	55.9%	66.0%	62.6%

(over open circle)

Label-richness preference. On some trials we asked participants to choose whether a perceptually bland or perceptually rich diagram best depicted the life cycle of an insect or a ladybug (manipulated within-subjects). There was an overall preference for the rich diagram. We predicted the probability of selecting the rich diagram from the category level of the label (coded 0.5 for insect and -0.5 for ladybug). The first model to converge included by-subject random intercepts and by-subject random slopes for category level, but did not allow the random effects to correlate. Participants were less likely to choose the rich diagram when asked to select a diagram that depicted the life cycle of an insect rather than the life cycle of a ladybug, $OR < 0.01$, Wald's $\chi^2 (1, N = 161) = 15.27$, $p < .001$. See Figure 3.

On some trials we showed participants a bland or a rich diagram and asked them if it depicted the life cycle of a ladybug or the life cycle of an insect. There was an overall trend to say that the diagrams depicted the life cycle of a ladybug. We predicted the probability of saying that the diagram depicted the life cycle of an insect from diagram type. The first model to converge included by-subject random slopes for diagram type. Participants were more likely to say that the diagram depicted the life cycle of an insect for the bland diagram than for the rich diagram, $OR = 290.32$, Wald's $\chi^2 (1, N = 161) = 27.73$, $p < .001$. See Figure 4.

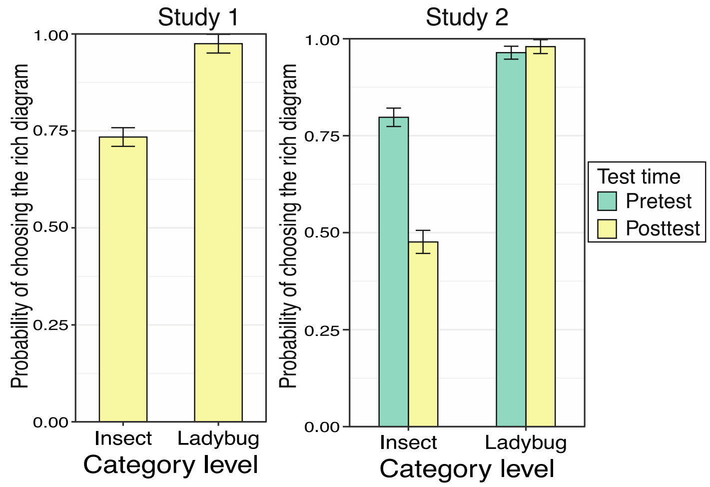


Figure 3. Model predictions of the probability of selecting the rich diagram over the bland diagram, separated by whether participants were asked to select a diagram for the life cycle of a ladybug or the life cycle of an insect. The left panel shows the results for Study 1 and the right panel shows the results for Study 2. Error bars show the within-subject standard errors of the point estimates.

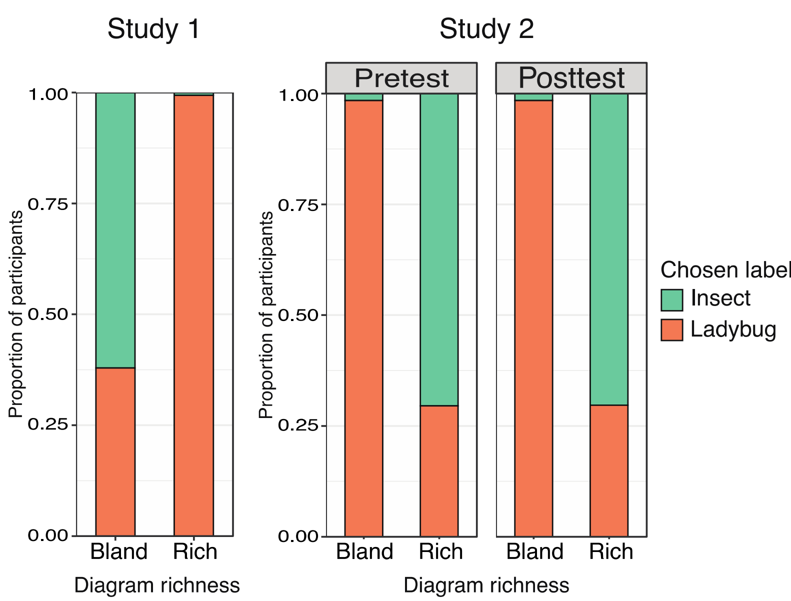


Figure 4. Proportion of participants who said the bland and rich diagrams depicted the life cycle of an insect or ladybug. The left-most panel shows the results for Study 1 and the middle and

right panels show the results for Study 2. For Study 2, we also separate participants' responses by whether they were provided at pretest (middle panel) or posttest (right panel).

Discussion

After a short exposure (less than 2 minutes) to diagrams with certain features, participants were more likely to draw diagrams that had those features, and they also preferred diagrams that had those features. Thus, even short experience with diagrams can shape people's expectations of how diagrams should look. Participants are clearly deciding which diagrams are the best representations and how to visually depict the life cycle stages, and we argue that experience with diagrams with particular features influences the decisions that participants make. Thus, this experience influences their representational skills.

However, it must be acknowledged that Study 1 has several limitations. First, because people were drawing different life cycles at pretest and posttest, it is possible that the differences that we saw in their drawings could be due to the animal that they were drawing. Second, we also do not know if these differences in drawing would persist over time. Third, because participants reported their preferences only at posttest, we do not know if the lesson made participants like linear diagrams more or if it reinforced an existing preference for circular diagrams. We address all of these limitations in Study 2 by (1) having participants draw the life cycles of butterflies and ladybugs at both pretest and posttest, (2) having participants draw the life cycle of a ladybug again at the end of the study to see if the differences by condition were still present after a short delay, and (3) having participants also completed the diagram preference task at both pretest and posttest. Thus, Study 2 serves as a replication of Study 1, while addressing possible confounding variables.

Study 2

Method

Participants

We recruited 195 undergraduate participants (116 women, 72 men, 1 other, 6 who did not report gender) from an Introduction to Psychology course at a large research university in the midwestern United States. The racial/ethnic breakdown of the sample was 54.3% White (n = 106), 26.2% Asian or Asian American (n = 51), 4.1% Hispanic or Latinx (n = 8), 2.0% Black or African American (n = 4), 0.5% Native American (n = 1), 0.5% Pacific Islander (n = 1), 0.5% Arab (n = 1), 0.5% other (n = 1), and 4.6% mixed or bi-racial (n = 9); 6.7% of participants did not respond (n = 13). Two participants were excluded because they did not pass the attention checks. Participants completed the study for extra credit.

Measures

All measures were the same as Study 1, except that we excluded the life cycle knowledge task.

Procedure

Participants completed the experimental tasks in the following order: (1) ladybug and butterfly drawing and explanation, (2) diagram preference and label-richness preference tasks, (3) randomly-assigned lesson with linear or circular diagram, (4) ladybug and butterfly drawing and explanation, (5) diagram preference and label-richness preference tasks, (6) ladybug drawing and explanation, (7) origin-of-species questions, and (8) demographic form. Two attention checks were also included, one after each diagram preference task.

Drawing coding

We used the same coding scheme as in Study 1. Reliability for all categories was acceptable and can be found in the supplemental materials. Reliability for coding the shape of the drawings was also acceptable ($\kappa = 0.85$).

Results

We followed the same data analytic strategy as in Study 1. We first present analyses of participants' drawings. Then, we present analyses of their diagram preferences followed by the label-richness preferences.

Drawing task. We predicted whether participants drew circular diagrams for the ladybug from test time (pretest, posttest, delayed posttest, with the posttest as the reference group), diagram condition, and their interaction. The first model to converge had by-subject random slopes for the effect of test time and did not allow the random effects to correlate. We found a significant effect of diagram condition, $OR = 3.74$, Wald's χ^2 $(1, N = 192) = 13.67$, $p < .001$, and a significant interaction between diagram condition and test time, Wald's χ^2 $(2, N = 192) = 11.94$, $p = .002$. As can be seen in Figure 5, participants who saw a circular diagram during the lesson were more likely to draw a circular diagram at posttest and after a delay.

We then predicted whether participants drew circular diagrams for the butterfly from test time (pretest, posttest), diagram type (linear, circular), and their interaction. The first model to converge had by-subject random intercepts and by-subject random slopes, but did not allow them to correlate. We found only a significant interaction between diagram condition and test time, $OR = 9.36$, Wald's χ^2 $(1, N = 192) = 10.63$, $p = .001$. As can be seen in Figure 5, participants who saw a circular diagram during the lesson were more likely to draw circular diagrams at posttest (even though they were never shown a butterfly life cycle during the lesson). Those who saw a linear diagram during the lesson were also more likely than those who saw a circular diagram to draw a linear diagram at posttest.

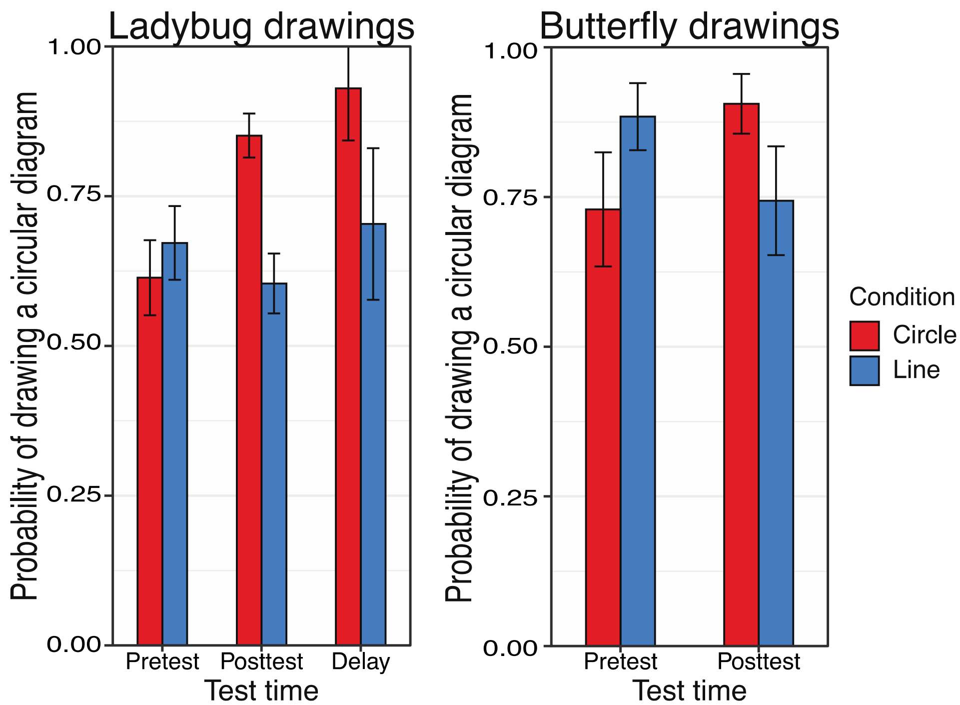


Figure 5. Probability of drawing a circular diagram at pretest, posttest, and delayed posttest by diagram condition. The left plot shows the results for ladybug drawings and the right plot shows the results for butterfly drawings. Error bars show the within-subject standard errors of the point estimates.

Diagram preference. As can be seen in Table 2, participants had similar preferences at pretest regardless of condition. We predicted participants' selection of the circular diagram (rather than the linear one) from diagram condition, test time (pretest, posttest), and their interaction. The first model to converge had by-subject random intercepts and by-subject random slopes for test time and allowed them to correlate. We found an effect of test time, *OR* = 1.71, Wald's χ^2 (1, *N* = 193) = 5.64, *p* = .017, and an interaction between diagram condition and test time, *OR* = 3.25, Wald's χ^2 (1, *N* = 193) = 9.15, *p* = .002, but no main effect of diagram condition, $OR = 1.36$, Wald's $\chi^2(1, N = 193) = 0.56$, $p = .453$. As can be seen in Figure 2, participants' preferences did not differ at pretest, but at posttest, those who saw the circular diagram in the lesson were more likely to select circular diagrams.

Label-richness preference. There was also an overall preference for the rich diagram. We predicted the probability of selecting the rich diagram from the category level of the label (coded 0.5 for insect and -0.5 for ladybug), test time and their interaction. The first model to converge had by-subject random slopes for the effect of category level, test time, and their interaction, and did not allow the random effects to correlate. We found an effect of category level, $OR = 0.04$, Wald's $\chi^2(1, N = 193) = 67.34$, $p < .001$, and an interaction between category level and test time, $OR = 0.10$, Wald's $\chi^2(1, N = 193) = 10.47$, $p = .001$. As can be seen in Figure 3, participants were less likely to choose the rich diagram when asked to select the diagram that best depicted the life cycle of an insect rather than the life cycle of a ladybug, and this trend was more pronounced at posttest than at pretest.

On some trials participants were asked to select the best label for a diagram. There was an overall trend to say that the diagram depicted the life cycle of a ladybug. We predicted the probability of saying that the diagram depicted the life cycle of an insect from diagram type, test time and their interaction. The first model to converge included random slopes for the effect of diagram type, test time, and their interaction, and did not allow the random effects to correlate. We found only an effect of diagram type; at both pretest and posttest participants were more likely to say that the diagram depicted the life cycle of an insect for the bland diagram than for the rich diagram, $OR = 1236.45$, Wald's $\chi^2(1, N = 161) = 71.32$, $p < .001$. See Figure 4.

General Discussion

These studies indicate that short exposure to diagrams with particular features can change people's preferences for those features and the prevalence of those features in visualizations they produce. This suggests that experience with particular diagrammatic features can influence students' representational skills in that they select and construct different visualizations after these experiences. Seeing a short lesson with a circular diagram led people to prefer other circular diagrams and to draw circular diagrams for the animal in the lesson and for other animals. The effect of this short intervention also persisted after a short delay. Our studies support the idea that students' experience with diagrams shapes their representational knowledge in a domain. These findings align with work on perceptual learning and suggest that explicit instruction about visualizations is not always needed for students to develop representational competence (Kellman et al., 2010).

Our studies also shed light on some of the mechanisms that underlie previous effects of visualizations on generalization. Specifically, Menendez et al. (2020) found that adults generalize more broadly if they receive a lesson with a bland diagram than if they receive a lesson with a rich diagram. We found that participants were more likely to say that bland diagrams represent the life cycle of an insect (a broader category) than the life cycle of a ladybug (a more specific category). This is the case even though either label is appropriate, as ladybugs are insects and thus the life cycle of a ladybug is by default the life cycle of an insect. Participants' responses in both studies suggest that they infer that blander diagrams refer to broader categories, while rich diagrams refer to the specific exemplar depicted. Thus, the greater generalization with bland diagrams found by Menendez et al. (2020) could be the result of participants inferring that the lesson applies more broadly when they see the bland diagram. Participants appear to use the richness of the diagram as a cue to infer the intended scope of generalization.

Implications for theories of multi-media learning

Scholars of multi-media learning have proposed that visualizations often provide a challenge for students, as they have to learn simultaneously how to interpret the visualizations and how to use visualizations to help them learn the lesson material (Rau, 2017b). Our study suggests that one way that students solve this challenge is by using their prior experiences with visualizations to guide their interpretations of new visualizations. These prior experiences might support students to more effectively extract meaning from visualizations with features they are used to seeing (Kellman et al., 2010; Kellman & Massey, 2013). Understanding these experiences is important as they might influence which diagrams benefit students the most (Menendez et al., 2022). Thus, these studies provide early support for the idea that experience with diagrams and visualizations can serve as the foundation for students' representational skills. These experiences provide students with information about how representations typically look in a domain, and what the elements embedded in those visualizations mean. This knowledge might serve as the foundation for the domain-specific representational skills that students bring to the classroom and use to interpret visualizations and support their learning.

Experience with diagrams may also help explain the mechanisms behind instructional techniques such as concreteness fading (also called the Concrete-Representational-Abstract sequence; Flores, 2010; Fyfe et al., 2014). In concreteness fading, students are first presented with a concrete, realistic representation of a concept. As they progress through the lesson, they are introduced to progressively more abstract and symbolic representations of the concept. Studies have found that teaching students with this progression leads to better learning and generalization of the concepts, compared to presenting the exact same representations but in the opposite order (Fyfe et al., 2015). Our studies suggest that this sequencing may work because it provides students with experiences with features of concrete representations that may guide their interpretations of abstract visualizations. Thus, by the time they encounter the abstract visualization, they are able to use their prior experiences with the concrete representation to correctly interpret the abstract one. Therefore, instructors could structure lessons to provide students with experiences with simpler visualizations in order to help them understand more complex visualizations.

It is worth mentioning that our findings do not diminish the importance of explicitly teaching students how to interpret visualizations. Several studies have shown that explicitly teaching students how to interpret visualizations can also foster representational competence (Kohl & Finkelstein, 2006; Rau, 2017a; Stieff, 2011; Stieff & DeSutter, 2020). Instead, our findings suggest that experiences with visualizations might be an alternative way for students to develop their representational competence. Future work should examine how learning about visualizations through experience and through instruction might lead to different knowledge, as students' exploration might not always lead to correct interpretations, and learning from instruction can lead students to miss key features (Bonawitz et al., 2011).

It is also important to highlight that there could be individual differences in how easily students make sense of visualizations. Students' preferences for learning with visual or auditory information (also called learning styles) seems unlikely to play a role, as studies have failed to show that these preference influence how much people learn (Nancekivell et al., 2020; Pashler et al., 2008). However, other individual difference factors, such as visuo-spatial ability, have been shown to influence how people learn with visualizations (Höffler, 2010). Students with high visuo-spatial ability might have an easier time making sense of visualizations, even without explicit instruction or with little prior experience.

Students' preferences might be shaped by factors other than experience and individual differences, such as the aesthetics or the clarity of the diagram. Although these factors likely influence participants' choices at pretest, they cannot account for the changes in participants' selections from pretest to posttest (and should be the same for participants regardless of their experimental condition), in the case of spatial arrangement, or for differences depending on category level, in the case of richness. Further, Study 1 showed that people learn equally well with linear and circular diagrams (and prior work has shown similar results for rich and bland diagrams, Menendez, Rosengren, et al., 2020), suggesting that the diagrams were similarly clear to college students.

Limitations

Our findings should be interpreted in light of the limitations of the studies. First, we focused on only one topic (metamorphosis), one type of visualization (life cycle diagrams), and manipulated one feature (spatial arrangement). It is possible that experience might play a lesser role in other domains or for other visualizations that are more complex.

Second, it is not clear whether the effects we observed will last for longer than a couple of minutes. Given that our lesson lasted less than two minutes, it seems likely that the effects might fade quickly. Future work should examine how quickly these effects fade, and whether the fading is related to the amount of exposure.

Finally, our studies were conducted online. There has been a rise in online instruction in recent years, but it is still unclear whether effects observed online will extend to classroom settings. Additionally, there is evidence suggesting that people plan and execute drawings differently in paper versus electronic media (Kirkorian et al., 2020). Therefore, participants' drawings in these studies might underestimate their skills when drawing on paper. However, it is worth noting that in these studies we focus mainly on the spatial arrangement of elements in the drawings, rather than on the quality of the drawings. Given that spatial arrangement can be conveyed using simple shapes and arrows, it is possible that the medium had a smaller effect than seen in previous studies. Future research should attempt to replicate these studies with students drawing on paper.

Conclusion

This work demonstrates that even brief experience with visualizations with different spatial arrangements leads to changes in the spatial arrangements that people prefer and produce. Thus, this work suggests that experience with visualizations contributes to representational competence. The findings raise new questions about the role of perceptual experience in acquiring representational competence. Further, this work suggests that, to better understand how students interpret and use visualizations, teachers would be well advised to consider—and to intentionally shape—students' experiences with visualizations.

References

Bartel, A. N., Silla, E. M., Vest, N. A., Nagashima, T., Aleven, V., & Alibali, M. W. (2021). Reasoning about Equations with Tape Diagrams: Insights from Math Teachers and College Students. In E. de Vries, Y. Hod, & J. Ahn (Eds.), *Proceedings of the International Conference of the Learning Sciences* (pp. 685–687).

Bonawitz, E., Shafto, P., Gweon, H., Goodman, N. D., Spelke, E., & Schulz, L. (2011). The double-edged sword of pedagogy: Instruction limits spontaneous exploration and discovery. *Cognition*, *120*(3), 322–330. https://doi.org/10.1016/j.cognition.2010.10.001

Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables that vary within-subjects and/or within-items. *Psychological Methods*, *23*(3), 389–411. https://doi.org/10.1037/met0000159

Carney, R. N., & Levin, J. R. (2001). Pictorial Illustrations Still Improve Students' Learning from Text. *Educational Psychology Review*, *14*(1), 5–26.

Cooper, J. L., Sidney, P. G., & Alibali, M. W. (2018). Who Benefits from Diagrams and Illustrations in Math Problems? Ability and Attitudes Matter: Diagrams and illustrations. *Applied Cognitive Psychology*, *32*(1), 24–38. https://doi.org/10.1002/acp.3371

diSessa, A. A., & Sherin, B. L. (2000). Meta-representation: An introduction. *The Journal of Mathematical Behavior*, *19*(4), 385–398. https://doi.org/10.1016/S0732-3123(01)00051-7

Fisher, A. V., Godwin, K. E., & Seltman, H. (2014). Visual Environment, Attention Allocation, and Learning in Young Children: When Too Much of a Good Thing May Be Bad. *Psychological Science*, *25*(7), 1362–1370. https://doi.org/10.1177/0956797614533801

Flores, M. M. (2010). Using the Concrete-Representational-Abstract Sequence to Teach Subtraction With Regrouping to Students at Risk for Failure. *Remedial and Special Education*, *31*(3), 195–207. https://doi.org/10.1177/0741932508327467

Fyfe, E. R., McNeil, N. M., & Borjas, S. (2015). Benefits of "concreteness fading" for children's mathematics understanding. *Learning and Instruction*, *35*, 104–120. https://doi.org/10.1016/j.learninstruc.2014.10.004

Fyfe, E. R., McNeil, N. M., Son, J. Y., & Goldstone, R. L. (2014). Concreteness Fading in Mathematics and Science Instruction: A Systematic Review. *Educational Psychology Review*, *26*(1), 9–25. https://doi.org/10.1007/s10648-014-9249-3

Gibson, E. J. (1963). Perceptual Learning. *Annual Review of Psychology*, *14*(1), 29–56. https://doi.org/10.1146/annurev.ps.14.020163.000333

Goldstone, R. L. (1998). Perceptual Learning. *Annual Review of Psychology*, *49*(1), 585–612. https://doi.org/10.1146/annurev.psych.49.1.585

Goldstone, R. L., Landy, D. H., & Son, J. Y. (2010). The Education of Perception. *Topics in Cognitive Science*, *2*(2), 265–284. https://doi.org/10.1111/j.1756-8765.2009.01055.x

Höffler, T. N. (2010). Spatial Ability: Its Influence on Learning with Visualizations—a Meta-Analytic Review. *Educational Psychology Review*, *22*(3), 245–269. https://doi.org/10.1007/s10648-010-9126-7

Horn, M. S., Phillips, B. C., Evans, E. M., Block, F., Diamond, J., & Shen, C. (2016). Visualizing biological data in museums: Visitor learning with an interactive tree of life exhibit. *Journal of Research in Science Teaching*, *53*(6), 895–918. https://doi.org/10.1002/tea.21318

Kellman, P. J., & Massey, C. M. (2013). Perceptual Learning, Cognition, and Expertise. In *Psychology of Learning and Motivation* (Vol. 58, pp. 117–165). Elsevier. https://doi.org/10.1016/B978-0-12-407237-4.00004-9

Kellman, P. J., Massey, C. M., & Son, J. Y. (2010). Perceptual Learning Modules in Mathematics: Enhancing Students' Pattern Recognition, Structure Extraction, and Fluency. *Topics in Cognitive Science*, *2*(2), 285–305. https://doi.org/10.1111/j.1756-8765.2009.01053.x

Kirkorian, H. L., Travers, B. G., Jiang, M. J., Choi, K., Rosengren, K. S., Pavalko, P., & Tolkin, E. (2020). Drawing Across Media: A Cross-Sectional Experiment on Preschoolers' Drawings Produced Using Traditional Versus Electronic Mediums. *Developmental Psychology*, *56*(1), 28–39. https://doi.org/10.1037/dev0000825

Kohl, P. B., & Finkelstein, N. D. (2006). Effects of representation on students solving physics problems: A fine-grained characterization. *Physical Review Special Topics - Physics Education Research*, *2*(1), 010106. https://doi.org/10.1103/PhysRevSTPER.2.010106

Kozma, R. B., & Russell, J. (1997). Multimedia and Understanding: Expert and Novice Responses to Different Representations of Chemical Phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968.

Lindner, M. A. (2020). Representational and decorative pictures in science and mathematics tests: Do they make a difference? *Learning and Instruction*, *68*, 101345. https://doi.org/10.1016/j.learninstruc.2020.101345

Mayer, R. E. (2008). Applying the science of learning: Evidence-based principles for the design of multimedia instruction. *American Psychologist*, *63*(8), 760–769. https://doi.org/10.1037/0003-066X.63.8.760

Menendez, D., Mathiaparanam, O. N., Liu, D., Seitz, V., Alibali, M. W., & Rosengren, K. S. (2020). Representing Variability: The Case of Life Cycle Diagrams. *CBE—Life Sciences Education*, *19*(3), ar49. https://doi.org/10.1187/cbe.19-11-0251

Menendez, D., Rosengren, K. S., & Alibali, M. W. (2020). Do details bug you? Effects of perceptual richness in learning about biological change. *Applied Cognitive Psychology*, *34*(5), 1101–1117. https://doi.org/10.1002/acp.3698

Menendez, D., Rosengren, K. S., & Alibali, M. W. (2022). Detailed bugs or bugging details? The influence of perceptual richness across elementary school years. *Journal of Experimental Child Psychology*, *213*, 105269. https://doi.org/10.1016/j.jecp.2021.105269

Nagashima, T., Bartel, A. N., Yadav, G., Tseng, S., Vest, N. A., Silla, E. M., Alibali, M. W., & Aleven, V. (2021). Using Anticipatory Diagrammatic Self-explanation to Support Learning and Performance in Early Algebra. In E. de Vries, J. Ahn, & Y. Hod (Eds.), *15th International Conference of the Learning Sciences* (pp. 474–481).

Nancekivell, S. E., Shah, P., & Gelman, S. A. (2020). Maybe they're born with it, or maybe it's experience: Toward a deeper understanding of the learning style myth. *Journal of Educational Psychology*, *112*(2), 221–235. https://doi.org/10.1037/edu0000366

Nitz, S., Ainsworth, S. E., Nerdel, C., & Prechtl, H. (2014). Do student perceptions of teaching predict the development of representational competence and biological knowledge? *Learning and Instruction*, *31*, 13–22. https://doi.org/10.1016/j.learninstruc.2013.12.003

Novick, L. R. (2006). The Importance of Both Diagrammatic Conventions and Domain-Specific Knowledge for Diagram Literacy in Science: The Hierarchy as an Illustrative Case. In D. Barker-Plummer, R. Cox, & N. Swoboda (Eds.), *Diagrammatic Representation and Inference* (Vol. 4045, pp. 1–11). Springer Berlin Heidelberg. https://doi.org/10.1007/11783183_1

Novick, L. R., Shade, C. K., & Catley, K. M. (2011). Linear Versus Branching Depictions of Evolutionary History: Implications for Diagram Design. *Topics in Cognitive Science*, *3*(3), 536–559. https://doi.org/10.1111/j.1756-8765.2009.01077.x

Pashler, H., McDaniel, M., Rohrer, D., & Bjork, R. (2008). Learning Styles: Concepts and Evidence. *Psychological Science in the Public Interest*, *9*(3), 105–119. https://doi.org/10.1111/j.1539-6053.2009.01038.x

Rau, M. A. (2017a). How do Students Learn to See Concepts in Visualizations? Social Learning Mechanisms with Physical and Virtual Representations. *Journal of Learning Analytics*, *4*(2), 240–263. https://doi.org/10.18608/jla.2017.42.16

Rau, M. A. (2017b). Conditions for the Effectiveness of Multiple Visual Representations in Enhancing STEM Learning. *Educational Psychology Review*, *29*(4), 717–761. https://doi.org/10.1007/s10648-016-9365-3

Schnotz, W. (2014). Integrated Model of Text and Picture Comprehension. In R. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (2nd ed., pp. 72–103). Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.006

Stieff, M. (2011). Improving representational competence using molecular simulations embedded in inquiry activities. *Journal of Research in Science Teaching*, *48*(10), 1137–1158. https://doi.org/10.1002/tea.20438

Stieff, M., & DeSutter, D. (2020). Sketching, not representational competence, predicts improved science learning. *Journal of Research in Science Teaching*, tea.21650. https://doi.org/10.1002/tea.21650

Tversky, B., & Jamalian, A. (2021). Thinking Tools: Gestures Change Thought About Time. *Topics in Cognitive Science*, *0*(0), 1–27. https://doi.org/10.1111/tops.12566

Wu, S. P. W., & Rau, M. A. (2018). Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations. *Learning and Instruction*, *55*, 93–104. https://doi.org/10.1016/j.learninstruc.2017.09.010