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Exploring an Online Simulation Before Lecture Improves Undergraduate Chemistry Learning

Marci S. DeCaro, Derek K. McClellan, Aleeta Powe, Danielle Franco, Raymond J. Chastain, Jeffrey L. Hieb, Linda Fuselier
marci.decaro@louisville.edu, derek.mcclellan@louisville.edu, aleeta.powe@louisville.edu
danielle.franco.1@louisville.edu, raymond.chastain@louisville.edu, jeff.hieb@louisville.edu, linda.fuselier@louisville.edu
University of Louisville

Abstract: This study tested whether exploring with simulations before instruction offers the conceptual benefits of "productive failure," compared to a more traditional lecture-then-practice method. Undergraduate students (*N*=218) in introductory chemistry courses completed an activity using an online simulation about atomic structure. Students either completed the simulation activity before (explore-first condition) or after (instruct-first condition) a lecture on the topic. Students in both conditions scored equally on an assessment of basic facts taught in the instruction. However, students in the explore-first condition scored significantly higher on assessments of conceptual understanding and transfer to a new concept, compared to students in the instruct-first condition. Students in the explore-first condition also reported experiencing greater competence and curiosity during the learning activities. A guided simulation activity prior to instruction can have both motivational benefits and deepen students' understanding.

Introduction

Exploratory Learning

Exploratory learning reverses the typical lecture-then-practice order of instruction, by giving students an exploration activity prior to direct instruction on the underlying topic. A growing number of studies have demonstrated that exploring before instruction improves students' conceptual understanding (Darabi et al., 2018; Loibl et al., 2017; Sinha & Kapur, 2021). Studies have also shown that students who explore first are better prepared for "future learning"— transferring their understanding to a related topic (Schwartz & Martin, 2004).

Completing a novel activity before instruction can be challenging, but also beneficial to learning. This process is considered "productive failure" for several reasons (Kapur, 2016). First, students consider what they already know about the content area, better integrating prior knowledge with the new knowledge (Newman & DeCaro, 2019). Second, students realize that they have gaps in their understanding—increasing the accuracy of their metacognition (Glogger-Frey et al., 2015) and heightening curiosity (Lamnina & Chase, 2019). Finally, students discern what features of the problems are, and are not, relevant to solving the problem (DeCaro & Rittle-Johnson, 2012; Glogger-Frey et al. 2015; Loibl et al., 2017; Schwartz & Martin, 2004).

Although exploratory learning has been shown to improve conceptual understanding, not all studies show this benefit (e.g., Chase & Klahr, 2017). More research is needed, in order to demonstrate when an exploration activity will benefit student learning or not. Additionally, little is known about whether activities that do not involve problem solving also have conceptual benefits when used as exploration activities.

Current study

The current study examined whether an online, interactive simulation benefits students' conceptual understanding when used as an exploration activity before a lecture, as opposed to practice after a lecture. *Interactive simulations* are graphically visualized representations of events, processes, and systems, designed to allow students to engage in scientific inquiry (Moser et al., 2017). When using a simulation, students can test hypotheses by systematically adjusting parameters and manipulating objects. Simulations have been increasingly accessible and popular to use in STEM classrooms (Blake & Scanlon, 2007). Despite their differences from the problem-solving activities typically used in exploratory learning, simulations present many of the same features thought to be useful (Kapur, 2016). For example, completing a simulation before instruction is potentially challenging but engaging, students can use prior knowledge to work on them, they offer feedback that can help students discern important problem features, and they include a wide problem space for students to explore.

In a controlled experimental design, students in undergraduate chemistry courses were randomly assigned to condition. Each condition included the same materials in different order. Students in the *explore-first condition* completed an online simulation activity on atomic structure, then were lectured on this topic. Students in the *instruct-first condition* completed lecture, then the simulation activity. All students then completed a survey assessing their perceptions of the learning activities. Finally, students completed a posttest assessing knowledge of facts directly taught during the lecture, targeted concepts, and transfer of knowledge to a new, related concept.

We hypothesized that the benefits of exploring before instruction would not be found on assessment of the taught facts, but rather on the conceptual and transfer items (e.g., Loibl et al., 2017; Schwartz & Martin, 2004). We also explored whether general motivational factors (situational interest, curiosity, self-efficacy, competence, belonging) would increase in the explore-first condition. Some prior studies have shown evidence of improved interest, but results have been mixed (e.g., Weaver et al., 2018), and most studies have not examined these factors. Such results would demonstrate that simulations can be used effectively as exploration. Moreover, conceptual changes may arise from a technique that is easy to implement, even in large undergraduate STEM courses.

Methods

Participants

Participants (N=218) were all undergraduate students (M_{age}=18.7, SD=2.38, 44.5% female) enrolled in two sections of an introductory chemistry course who completed both the simulation activity and posttest. Additional students were excluded from analyses for not attending the full class session (5 students), or for illegible writing on the posttest that precluded scoring (1 student).

Materials

The class sessions included four phases that varied in order: simulation activity, lecture, survey, and posttest. Students in the *instruct-first condition* (n=116) completed the lecture, then the simulation activity. Students in the *explore-first condition* (n=102) completed the simulation activity, then the lecture.

In the *simulation activity*, students explored the *Build an Atom* Physics Education Technology (PhET) interactive simulation (https://phet.colorado.edu/en/simulations/build-an-atom) using their own devices. Students were given a worksheet to guide their exploration, and most students worked individually. The worksheet consisted of brief instructions on how to operate the simulation, followed by guiding questions (e.g., Place a neutron in the nucleus. What is the name of the element?"). In the *lecture*, the course professor gave direct instruction on the topic of atomic structure accompanied by presentation slides. The lecture began by introducing the basics of atoms, followed by description of atomic structure, isotopes, and atom identity.

Survey items assessed motivational factors related to the learning activities, using a 5-point Likert scale (1=*Strongly Disagree*, 5=*Strongly Agree*). Items assessed students' perceived *self-efficacy* (2 items, α=.72; adapted from Findley-Van Nostrand & Pollenz, 2017; e.g., "I feel confident in my ability to learn these kinds of topics"), *competence* (2 items, α=.37; Findley-Van Nostrand & Pollenz, 2017; e.g., Thanks to today's learning activities, I feel more competent in this topic area), *situational interest* (3 items, α=.62; Rotgans & Schmidt, 2014, e.g., "I enjoyed working on these activities"), *curiosity* (3 items, α=.60; Naylor, 1981; e.g., "I want to know more about what I was working on"), and *prospective belonging uncertainty* (4 items, α=.82; adapted from Walton & Cohen, 2011; e.g., "Sometimes I worry that I do not belong in college." The belonging items were reverse coded, so that higher scores reflected greater perceived belonging. Next, students completed the *Mental Effort Rating Scale*, a measure of cognitive load (1 item; Paas, 1992; "In completing the learning activities I invested…"). This item was rated on a scale from 1 (*very, very low mental effort)* to 9 (*very, very high mental effort*). Additional survey items were not included in the current report. Finally, students provided demographic information.

The *posttest* included 12 open-ended questions developed by two content experts (chemistry professors). Six items assessed facts taught during the lecture (6 points; α=.76; e.g., "What is the name of the particle that has no charge?"). Five items targeted conceptual knowledge (10 points; α=.31; e.g., "Explain the difference between an atom and an ion"). One item tested knowledge transfer (2 points; "What is the charge of an ion that has 12 protons and 13 electrons? Explain your answer").

Procedure

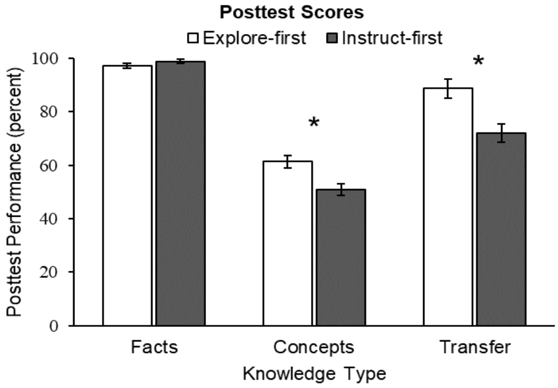
Students were enrolled in two sections of an introductory chemistry course, taught by the same professor in large lecture halls. Each course section was randomly divided into two groups and asked to attend on Wednesday (instruct-first condition; n=102) or Friday (explore-first condition; n=116), in a 50-min session. The explore-first condition began with the simulation activity (approximately 15 min), then the lecture (approximately 15 min). The instruct-first condition completed the lecture then simulation activity. Then, students completed the questionnaire (5 min) and posttest (10-15 min) on paper, without computers or notes. Students were told that responses would not be graded and assessed how they learned from the activities. Weeks later, the instructor sent a debriefing email with the option to withdraw data. All procedures were approved by the university IRB.

Results

Learning Outcomes

Posttest scores were examined using a 2 (*instruction order*: explore-first, instruct-first) × 2 (*knowledge type*: facts, concepts) mixed-factorial analysis of variance (ANOVA), with instruction order between-subjects and knowledge type within-subjects. A significant main effect of instruction order was found, $F(1,216)=5.63$, $p=.018$, $\eta_p^2=.03$. On average, posttest scores were higher for students in the explore-first condition (M=79.22%, SE=1.31) than in the instruct-first condition (M =74.94%, SE=1.23). There was also a significant main effect of knowledge type, $F(1,216)=649.82$, $p<.001$, $\eta_p^2=.75$, with higher scores on questions assessing basic facts (M=97.96%, SE=0.63) than concepts (M=56.20, SE=1.60). These effects were qualified by a significant interaction, $F(1,216)=13.71$, $p<.001$, $\eta_p^2=.06$ (Figure 1). Follow-up ANOVAs revealed that fact knowledge scores were not significantly different between the explore-first (M=97.06% SE=0.91, *95% CI*[95.28, 98.86]) and instruct-first (M=98.85%, SE=0.86, *95% CI* [97.16, 100.54]) conditions, $F(1,216)=2.05$, $p=.154$, $\eta_p^2=.01$. Concept knowledge scores were significantly higher in the explore-first (M=61.37%, SE=2.34, *95% CI*[56.76, 65.98]) than the instruct-first condition (M=51.03%, SE=2.19, *95% CI*[46.71, 55.36]), $F(1,216)=10.40$, $p<.001$, $\eta_p^2=.05$. A separate ANOVA demonstrated that students in the explore-first condition (M=88.73%, SE=3.63) scored higher on transfer than those in the instruct-first condition (M=71.98%, SE=3.41), $F(1,216)=11.29$, $p=.001$, $\eta_p^2=.05$.

Figure 1
Posttest scores as a function of knowledge type and order of instruction. Error bars = ± 1 SE.



Survey

Instruction order had no impact on reported cognitive load (Table 1), $F(1,209)=1.61$, $p=.207$; by the end of the class session, students in the explore-first condition did not perceive higher mental effort. To assess differences between instruction orders on the other survey items, a MANOVA was used. A significant overall effect of instruction order was found, $F(5,174)= 2.89$, $p=.016$; Wilks' $\Lambda=.923$, $\eta_p^2= .08$. On average, students in the explore-first condition rated these measures as higher than the instruct-first condition. Examining each scale, significant differences were found for curiosity, $F(1,178)=4.81$, $p=.030$, $\eta_p^2=.03$, and competence, $F(1,178)=6.04$, $p=.001$, $\eta_p^2= .06$ (Table 1).

Table 1 *Descriptive Statistics for Survey Subscales*

	Explore-First			*Instruct-First*		
	M	*SE*	*95% CI*	*M*	*SE*	*95% CI*
Cognitive Load	5.51	0.15	5.21–5.80	5.24	0.14	4.96–5.52
Self-efficacy	4.35	0.05	4.24–4.46	4.28	0.06	4.16–4.39
Belonging	4.04	0.08	3.88–4.20	3.98	0.09	3.81–4.15
Curiosity	**3.79**	**0.05**	**3.68–3.89**	**3.58**	**0.08**	**3.41–3.74**
Competence	**3.78**	**0.08**	**3.63–3.92**	**3.41**	**0.09**	**3.24–3.57**
Situational Interest	3.97	0.06	3.85–4.08	3.86	0.07	3.71–4.01

Note: Bold=statistically significant at p<.05. Cognitive load 9-point scale; all others 5-point scale.

Discussion

Students given a guided simulation activity before lecture in an undergraduate chemistry course scored higher on assessments of concept knowledge, and transfer to a new concept, compared to completing the same simulation activity after instruction. Students in the explore-first condition also showed motivational benefits, with higher ratings of curiosity and competence. Motivation often predicts desire to continue learning about a topic (Deci & Ryan, 2000). These results suggest that exploratory learning may have benefits for future learning and persistence.

These findings expand the exploratory learning literature by examining the impact of using simulations, rather than problem-solving activities, as exploration activities before lecture. These results also extend this research to an undergraduate chemistry course. This research used a controlled classroom experiment, manipulating only the order of the activity and lecture, demonstrating a causal effect. Materials were created and administered by chemistry professors, increasing ecological validity.

More research is needed to replicate these findings, with other types of simulations, learning domains, and other instructors. One limitation is that the instruct-first condition was given earlier in the week than the explore-first condition, thus the professor may have become more fluent in giving the lecture. However, the professor had taught this course for many years, reducing the likelihood of practice effects.

Simulations are becoming increasingly accessible in STEM courses. These results suggest that a minor change in the timing of these simulations—given before, rather than after, instruction—can deepen students' understanding and support their perceived competence and curiosity for the information.

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