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Inter-level Scaffolding and Sequences of Representational Activities in Teaching a Chemical System with Graphical Simulations

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Abstract Chemistry knowledge can be represented at macro-, micro- and symbolic levels, and learning a chemistry topic requires students to engage in multiple representational activities. This study focused on scaffolding for inter-level connection-making in learning chemistry knowledge with graphical simulations. We also tested whether different sequences of representational activities produced different student learning outcomes in learning a chemistry topic. A sample of 129 seventh graders participated in this study. In a simulation-based environment, participants completed three representational activities to learn several ideal gas law concepts. We conducted a 2 × 3 factorial design experiment. We compared two scaffolding conditions: (1) the *inter-level* scaffolding condition in which participants received inter-level questions and experienced the dynamic link function in the simulation-based environment and (2) the *intra-level* scaffolding condition in which participants received intra-level questions and did not experience the dynamic link function. We also compared three different sequences of representational activities: macro-symbolic-micro, micro-symbolic-macro and symbolic-micro-macro. For the scaffolding variable, we found that the *inter-level* scaffolding condition produced significantly better performance in both knowledge comprehension and application, compared to the *intra-level* scaffolding condition. For the sequence variable, we found that the macro-symbolic-micro sequence produced significantly better knowledge comprehension performance than the other two sequences; however, it did not benefit knowledge application performance. There was a trend that the treatment group who experienced *inter-level* scaffolding and the micro-symbolic-macro sequence achieved the best knowledge application performance.

Keywords Chemistry learning · Scaffolding · Sequence of representational activities · Simulation-based environment

Introduction

Chemistry knowledge is represented and communicated at macro-, micro- and symbolic levels (Gilbert and Treagust 2009; Johnstone 1982, 2000). Based on Johnstone's (1982) definitions, a macro-level refers to a phenomenon that is observable and experiential, for example, an observation of an over-inflated tire that pops on a summer day. A micro-level refers to a particulate model that explains certain macro-level phenomena, for example, a simulation that visualizes molecules moving randomly and bouncing off container walls. A symbolic level refers to conventionally accepted symbols, equations, formulas and abstract graphs that denote concepts or model relationships underlying some chemical phenomena, for example, the ideal gas law and a chemical reaction equation.

Knowledge about the particulate nature of matter plays a pivotal role in understanding abstract chemistry topics (Çalik and Ayas 2005; Nakhleh 1992; Snir et al. 2003) such as gas (Stavy 1988), matter phase change (Tsai 1999) and solution (de Vos and Verdonk 1996). The ability to scientifically represent and explain the micro-level dynamics of a chemical system is necessary for students to

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comprehend the macro-level behaviors of the system and to connect the multi-level chemistry knowledge (Levy 2013).

A significant amount of literature has documented students' difficulties in understanding the particulate theory (e.g., Çalik and Ayas 2005; Ayas et al. 2010; Levy 2013) and in connecting different levels of chemistry knowledge (e.g., Gilbert and Treagust 2009; Jaber and Boujaoude 2012). For example, students often ignore micro-level and symbolic-level knowledge in explaining macro-level phenomena when learning chemistry (Ardac and Akaygun 2004; Gilbert and Treagust 2009).

Gas is a representative topic that students have difficulties learning due to a lack of scientific micro-level knowledge and inability to connect multiple levels (Çalik and Ayas 2005; Kautz et al. 2005; Mas et al. 1987; Stavy 1988). Common preconceptions about gas are, for example, "air is a continuous substance," "gas behavior is similar to liquid behavior" and "there is little space between gas particles" (Ayas et al. 2010; Benson et al. 1993). These preconceptions about the micro-level make the comprehension of macro-level gas properties and behaviors extremely difficult, for example, even college students have difficulties understanding the ideal gas law (Kautz et al. 2005). Additionally, macro-level gas behaviors such as pressure change are abstract and are often represented symbolically with abstract graphs and equations, which makes learning more difficult (Kautz et al. 2005).

To scientifically explain an ideal gas law phenomenon, students need to have a correct understanding of dynamic molecular behaviors, for example, "random movement of gas molecules," "collective motion of gas molecules" and "forever motion and bouncing behaviors" (Levy and Wilensky 2009). Students also need to connect micro-level dynamics to macro-level gas properties, for example, understanding that pressure is an emergent phenomenon that arises from molecule-container collision. We selected the ideal gas law as the learning topic in this study because it is a representative topic for which students need to understand the particulate nature of gas and connect multiple levels.

Constructing multi-level chemistry knowledge involves learning with multiple external representations (Wu and Puntambekar 2012). Simulation-based environments are effective tools for chemistry learning, because they have strong visualization power and are convenient for presenting multiple dynamic representations that depict, illustrate or explain macro-, symbolic and micro-levels of a chemistry topic (Levy 2013; Russell et al. 2000; Wu et al. 2001; Zhang and Linn 2013). However, research has suggested that without proper scaffolding, students may not benefit from the multiple dynamic representations in a simulation-based environment (e.g., Ainsworth 2006; van der Meij and de Jong 2006); therefore, this study focuses on the scaffolding variable in learning multi-level chemistry knowledge with graphical simulations.

Literature Review

Learning Chemistry in Simulation-Based Environments

Simulation-based environments are effective tools for learning chemistry, because graphical simulations can visualize micro-level dynamics in a concrete manner, and they are convenient for delivering multiple dynamic representations in different formats depicting, illustrating or explaining multiple levels of knowledge (Chang et al. 2010; Levy 2013; Russell et al. 2000; Stieff and Wilensky 2003; Wu et al. 2001). One good example is the SMV-chem program introduced by Russell et al. (2000), which includes four external representations of heat exchange equilibrium: a realistic video of a laboratory experiment (macro-level), a simulation demonstrating molecular activities (micro-level), a dynamic graph showing the relationship between temperature change and equilibrium (symbolic level) and a text-based explanation of the abstract principle (symbolic level).

A variety of representational activities can be designed to promote knowledge construction in a simulation-based environment. In this paper, a representational activity refers to questions/tasks around representation(s) that require students' undertakings, which defines how the representation(s) should be learned or generated, for example, exploring, manipulating, observing and describing dynamic representations (Kozma 2000) and answering self-explanation prompts (Chi and Wylie 2014). In addition to learning presented representations, students also need opportunities to generate representations, which is an effective representational activity (Kozma and Russell 2005). Simulation-based environments can provide resources for representation generation (Zhang and Linn 2013), for instance, a simulation may produce sets of numerical data as students manipulate variables, which students can use for plotting a chart to explain an abstract relationship (Plass et al. 2009), and a drawing space can provide drawing primitives (e.g., balls that represent atoms, lines that represent bonds) which students can manipulate to create particulate models (Zhang and Linn 2013).

Inter-level Scaffolding

Enacting multiple dynamic representations that depict, illustrate and explain multiple levels of knowledge can be cognitively demanding, and abundant research has suggested the importance of scaffolding for learning chemistry in a simulation-based environment (e.g., Chiu and Linn 2014; Russell et al. 2000).

As students learn multiple levels of chemistry knowledge sequentially, major learning difficulties students encounter are to connect and transition across macro-, micro- and symbolic levels (Gilbert and Treagust 2009; Jaber and Boujaoude 2012; Johnstone 2000; Kozma 2003; Treagust et al. 2003); therefore, in a simulation-based environment, how to scaffold connection-making across different levels is a critical pedagogical question (Ainsworth 2008; Chiu and Linn 2014). Inter-level scaffolding, defined as techniques that help students make connections among multiple levels (Levy and Wilensky 2009), facilitates knowledge construction (Chiu and Linn 2014) and also helps students reason micro-to-macro emergent causality in chemical systems (Jacobson and Wilensky 2006; Levy and Wilensky 2009).

The following two sections discuss two inter-level scaffolding techniques that are often applied in simulation-based environments teaching complex science topics: (1) dynamic link of representations, (2) inter-level questions.

Dynamic Link of Representations

The dynamic link refers to the function that allows multiple dynamic representations to change simultaneously, that is, as one operates on one dynamic representation, other representation(s) change accordingly (van der Meij and de Jong 2006). The function of the dynamic link can potentially guide students to see the connections among multiple representations, therefore, bridging different levels of knowledge (Ainsworth 2006, 2008). For example, in Russell et al. (2000), students viewed a video of the heat exchange equilibrium and a molecular simulation changing simultaneously. This allows students to see the connections between the macro-level phenomenon and the micro-level molecular behaviors.

Dynamically linked representations may also provide an experience of emergent causality between a micro- and a macro-level. For example, in Chi, Roscoe, Slotta, Roy and Chase (2012), a macro-simulation and a micro-simulation of diffusion occurring simultaneously allowed students to analyze how random movement of water and ink molecules at the micro-level caused directional macro-level “ink flow” phenomenon.

Inter-level Questions

Cognitive and metacognitive demand can be overwhelming for novice learners when learning multiple dynamically linked representations (van der Meij and de Jong 2006); therefore, students benefit from scaffolding questions that facilitate self-explanation for deep understanding (Berthold and Renkl 2009; Chi and Wylie 2014).

A scaffolding question may require students to construct knowledge of one level or to integrate knowledge across levels. In this paper, like Levy and Wilensky (2009), we distinguish scaffolding questions that target at connection-making across different levels, defined as inter-level questions, from scaffolding questions that require one to explain concepts of a single level, defined as intra-level questions. For example, in learning ideal gas law concepts, an inter-level question may ask students to use the molecular behaviors illustrated in a simulation to explain why the gas pressure changes in an abstract diagram, whereas an intra-level question about the micro-level may ask students to explain how molecules behave in the simulation.

Because students have the most difficulty in bridging different levels of chemistry knowledge (e.g., Gilbert and Treagust 2009), it is reasonable to emphasize the importance of inter-level questions in chemistry learning. Inter-level questions are often applied in instruction and environment design for successful connection-making and knowledge construction (e.g., Chiu and Linn 2014; Levy and Wilensky 2009). Levy and Wilensky (2009) argue that inter-level questions help students visualize emergent processes from a micro-level to a macro-level.

Dynamic link of representations and inter-level questions are two popular inter-level scaffolding techniques (Wu and Shah 2004); however, previous research that applied these techniques in teaching chemistry often used a one-group design or involved a control group that differed from an experimental group in many other aspects, for instance, the representational environment, the number of representations and the total amount of scaffolding. In this study, we attempted to study the effects of *inter-level* scaffolding *per se* on learning a chemical system, by comparing it to a condition that received the same representations and a comparable amount of *intra-level* scaffolding.

Procedural Scaffolding: Sequencing Representational Activities

Learning chemistry requires students to complete a variety of representational activities. Procedural scaffolding with regard to how to properly sequence these activities is another important pedagogical question (Quintana et al. 2004; Wu and Puntambekar 2012).

As discussed earlier, chemistry knowledge is taught at macro-, micro- and symbolic levels. How to better sequence representational activities teaching different levels of a chemistry topic is unclear (Wu and Puntambekar 2012). Regardless, prior research engenders some implications and hypotheses for this question. First, symbolic-level knowledge is usually abstract and difficult for conceptual understanding without any grounding knowledge (Tsaparlis 2009). The first idea suggests that learning symbolic-level knowledge first is not effective for novice learners. Second, symbolic-level knowledge defines and models phenomena, therefore, is critical for bridging macro- and micro-levels (Taber 2013). The second idea implies that a representational activity for a symbolic level can be delivered between activities for macro-level and micro-level knowledge. Third, previous research suggests that a "concrete to abstract" sequence benefits learning complex science knowledge (Corradi et al. 2015; Goldstone and Son 2005). The second idea and third idea together suggest that macro-symbolic-micro can be a good sequence to deliver representational activities. Fourth, some research on model progression suggests that learning a primitive micro model first helps students understand an aggregated model represented symbolically (Frederiksen et al. 1999) and allows students to experience emergent causality (Levy and Wilensky 2009). For example, Frederiksen et al. (1999) argue that learning a primitive micro model of electrons first helps students derive the linkages between the micro model and the aggregated algebraic equations representing electric current concepts. The second idea and fourth idea together suggest that micro-symbolic-macro may also be an effective sequence to deliver representational activities.

In this study, in addition to testing the effects of *inter-level* scaffolding, we also compared the effects of three different sequences of representational activities on students' learning performance, including macro-symbolic-micro, micro-symbolic-macro and symbolic-micro-macro.

Summary

Multi-level chemistry knowledge is communicated and taught with multiple external representations, and learning chemistry involves engaging in a variety of representational activities. Simulation-based environments are effective tools for chemistry learning because they are convenient in visualizing abstract concepts and delivering multiple external representations for knowledge construction. *Inter-level* scaffolding techniques such as dynamic link of simulations and inter-level questions are often applied in teaching chemistry; however, previous research studying *inter-level* scaffolding techniques often involved a one-group design or a control group that also differed in many other aspects. Therefore, the major goal of this study was to empirically test the effects of *inter-level* scaffolding *per se* on learning outcomes by including a control condition that received similar amount of information. How to sequence representational activities in teaching chemistry is an important but not fully answered question in chemistry education. Therefore, in this study, we also tested whether different sequences of representational activities produced different learning outcomes.

Research Questions

- *Research Question 1* Does *inter-level* scaffolding benefit learning a chemistry topic more than *intra-level* scaffolding?
- *Research Question 2* Which sequence of representational activities produces the best performance in learning a chemistry topic, macro-symbolic-micro, micro-symbolic-macro or symbolic-micro-macro?

Methods

Participants

A sample of 129 seventh graders from two public urban middle schools participated in this study. We dropped six cases due to the absence of participants during the learning session or the posttest. The final sample included 123 participants. There were 78.9 % of the participants who identified themselves as Hispanic, 13.8 % as black, 4.1 % as white and 3.3 % as other. The mean age of this sample was 12.4 (SD = 0.53). There were 48.8 % who were male and 51.2 % who were female. This sample came from low socioeconomic status (SES) families, with 91 % of the population in the first school and 75 % of the population in the second school eligible for free or reduced lunch.

Learning Topic: Ideal Gas Law

As discussed in the introduction, the idea gas law is a representative topic for which students have difficulties connecting multiple levels. In this study, we focused on teaching the relationship between gas temperature and gas pressure with constant volume. We applied the "technology-enhanced inquiry-based" learning model (Linn et al. 2004; Çalik et al. 2010) in our instruction. Students were expected to complete three representational activities with simulations and assembled worksheets.

Simulations

An "aerosol can" simulation and a "container of molecules" simulation were used in this study.[1] Figure 1 is a

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[1] This simulation-based environment includes three phenomenon simulations that illustrate three gas phenomena corresponding to the three laws (the Gay-Lussac's law, the Boyle's law and the Charles' law) and one "container of molecules" simulation in which students can manipulate to learn the relationships among temperature, pressure and volume variables as well as view molecular behaviors under different conditions. In this study, students were expected to learn the temperature–pressure relationship when volume stayed constant (the Gay-Lussac's law); thus, they only learned one phenomenon

Fig. 1 "Aerosol can" simulation

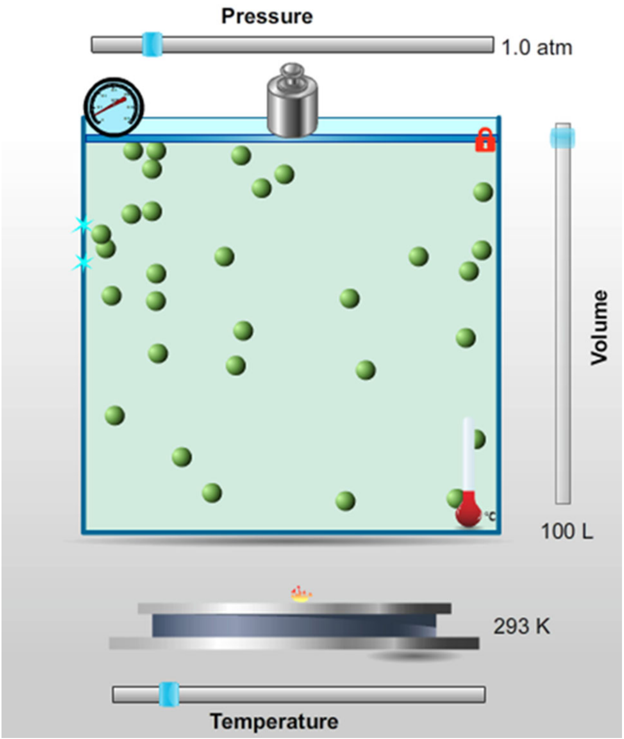


Fig. 2 "Container of molecules" simulation

snapshot of the "aerosol can" simulation; when one moves the fire icon toward the bottom of the can, one would see the can shakes faster and faster until it explodes. Figure 2 is a snapshot of the "container of molecules" simulation; one may manipulate the temperature variable and observe gas molecular behaviors (e.g., random movement, speed change of molecules, molecule–molecule and molecule-wall collisions) under different temperatures. The "container of molecules" simulation also generates sets of numeric values of the temperature and pressure variable (the values are displayed near each variable slider).

When the dynamic link function is turned off, the two simulations are displayed on two separate pages, and one may click an arrow button that directs to either simulation. Once the dynamic link function is turned on, the two simulations are displayed on the same page and change simultaneously (see Fig. 3 for a snapshot of two simulations dynamically linked). When one manipulates the fire icon in the "aerosol can" simulation, the values of the temperature and pressure variable and the molecular activity would also change accordingly in the "container of molecules" simulation, and vice versa.

The two simulations are structurally and functionally mapped. Structurally, the fire icon in the "aerosol can" simulation is placed under the can and the temperature slider in the "container of molecules" simulation is placed under the container; the aerosol can and the container of molecules are both vertically placed. Functionally, moving the fire icon up in the "aerosol can" simulation makes the can shake faster with the can size stays the same; meanwhile, moving the temperature to a higher value in the "container of molecules" simulation results in the molecules moving faster, and the pressure value increasing, while the volume staying the same. Structural–functional mapped representations allow students to make analogical comparisons (Gentner and Markman 1997).

Assembled Worksheets

The assembled worksheets contained (1) guidance for navigating the environment and using the two simulations, (2) questions/tasks for three representational activities and (3) scaffolding questions (either inter-level or intra-level questions depending on the scaffolding condition).

The design of the representational activities followed principles for constructive learning (Chi and Wylie 2014; Berthold and Renkl 2009). In each representational activity, we engaged participants with a concrete simulation. The questions/tasks for the representational activities delivered in the worksheets required participants to explore the chemical system by manipulating the simulation and to explain and elaborate their understanding.

Footnote 1 continued
simulation (i.e., "aerosol can" simulation) and the volume variable was set constant in the "container of molecules" simulation.

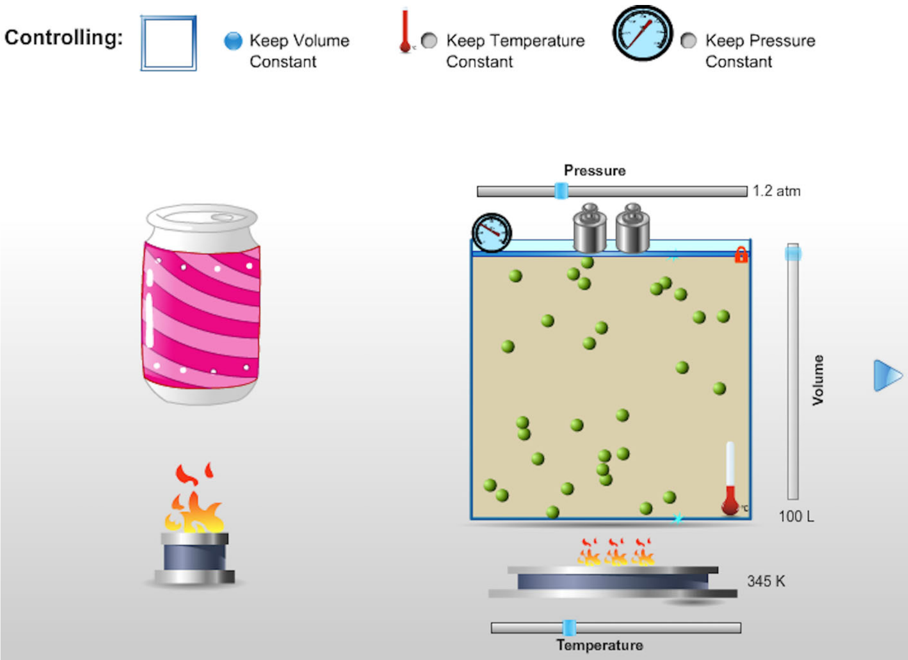


Fig. 3 Two simulations dynamically linked

The questions/tasks included prediction, data collection and analysis, self-explanation and representation generation. We label the three representational activities as *macro*, *symbolic*, and *micro,* respectively, because they focused on the three knowledge levels of the chemical system.

- *Macro* activity: describing and explaining a macro-level phenomenon with the help of the "aerosol can" simulation. The *macro* activity included two questions asking participants to manipulate the "aerosol can" simulation, describe and explain the can explosion phenomenon.
- *Symbolic* activity: generating symbolic-mathematical representations of temperature–pressure relationship with the help of the "container of molecules" simulation. We applied the Predict-Observe-Explain pedagogical strategy (White and Gunstone 1992) in designing this representational activity, which contained four steps: (1) predicting the relationship between temperature and pressure when the volume is constant, (2) manipulating the temperature variable to observe changes in the pressure variable in the simulation, collecting and recording five sets of values for temperature, pressure and volume in a data table, (3) graphing the numeric data to generate a line graph, (4) analyzing the numeric data and the line graph to generate a verbal explanation about temperature–pressure relationship when volume remained constant.
- *Micro* activity: describing and explaining micro-level dynamics with the help of the "container of molecules" simulation. The questions/tasks for the *micro* activity included three open-ended questions, one multiple-choice question and one estimation question (i.e., estimate the frequency of molecules hitting the container wall at different temperatures). These questions/tasks required participants to observe and explain molecular behaviors.

Appendix 1 contains sample questions/tasks for the three representational activities.

In addition to the three representational activities, depending on the scaffolding condition, participants received either inter-level scaffolding questions or intra-level scaffolding questions in the assembled worksheets. There were three inter-level questions, one targeted at linking the macro-level and symbolic level, one targeted at linking the micro-level and symbolic level and one targeted at linking knowledge of all three levels. An inter-level question not only asked participants to explain knowledge of a level but also explicitly required them to use knowledge from one level to explain concepts of another level.

There were seven intra-level questions in total including three questions on the macro-level, two questions on the symbolic level and two questions on the micro-level. An intra-level question asked participants to explain knowledge of a single level but did not explicitly require them to make connections across levels.

We manipulated the inter-level questions and intra-level questions so that the two sets of questions contained a comparable amount of information, and both required participants to generate self-explanations. Table 1 lists the two sets of scaffolding questions.

Table 1 Inter-level questions vs. intra-level questions

Inter-level questions	Intra-level questions
1. What is the relationship between temperature and pressure? Use what you learned about temperature and pressure from the gas container presentation and explain why the aerosol can explodes. (linking macro- and symbolic level)	1. Explain why the aerosol can explodes. (macro)
2. How do gas molecules behave? Use what you learned about gas molecules; explain why as temperature rises, pressure inside the container also rises. (linking symbolic level and micro-level)	2. Use what you learned about temperature and pressure from the gas container presentation and explain what is the relationship between temperature and pressure. (symbolic)
3. Use the knowledge of gas molecules; explain what happens to the gas pressure inside the aerosol can as you drag the fire closer. Explain why the aerosol can explodes. (linking macro-, symbolic and micro-level)	3. Use the knowledge of gas molecules; explain how do gas molecules behave. (micro)
	Four additional intra-level questions:
	4. Explain what happens to the aerosol can as you drag the fire closer. (macro)
	5. What did you learn from the aerosol can presentation? (macro)
	6. As temperature rises, pressure also rises, is this correct? (symbolic)
	7. What did you learn about gas molecules? (micro)

The technology-embedded scientific inquiry (TESI) model (Çalik 2013) suggests that when a variety of techniques and technological tools are integrated into a science inquiry model, the effects on learning performance pertain to the learning model rather than specific techniques or technological tools. In this study, although our instruction included a variety of components including two simulations, a variety of questions/tasks in the representational activities and inter-level or intra-level scaffolding questions, these components were integrated to emphasize two aspects of scientific inquiry including scientific conceptualization, which emphasizes "understanding, testing and clarifying ideas," and scientific investigation, which focuses on "generating questions or hypotheses, designing experiments and conducting investigation" (Çalik 2013).

Measures

Pretest

The pretest included one multiple-choice question and two open-ended questions asking participants to explain two idea gas law phenomena: "why using an ice pack reduces tooth pain caused by a tiny space filled with gas in an infected tooth" and "why car tires are more likely to pop in summer than in winter."

Posttest

The posttest included two subtests: a comprehension test and an application test. The comprehension test contained two filling-in-blank questions, one labeling task and five open-ended questions. The application test contained the same questions from the pretest. See Appendix 2 for the pre- and posttest questions. The posttest measured the first three levels of learning in the Bloom's taxonomy, that is, "remember," "understand" and "apply" (Anderson and Krathwohl 2001). The first three questions of the comprehension test measured if participants could remember the following basic concepts: What is gas composed of, how do gas molecules behave and interact, and how is gas temperature, pressure and volume measured and described in an experiment. The other four questions in the comprehension test required participants to generate their own explanations of the learned gas phenomena (aerosol can problem), the abstract concept of gas pressure and the relationship between temperature and pressure of the ideal gas. Based on the Bloom's taxonomy, generating self-explanations requires an understanding of the learned concepts. The multiple-choice question and two open-ended questions in the application test required participants to apply their knowledge of the ideal gas law to explain two different gas phenomena that were not learned. Because participants did not have much prior knowledge about the ideal gas law before the instruction and the learning session was relatively short (a limitation to be explained and discussed later), we did not expect them to acquire a higher level of understanding than "apply."

We took two strategies to increase the validity and reliability of the measures. First, to ensure the face validity and readability, we invited two professors in Education, a group of graduate researchers working on their doctoral degrees, and two middle school science teachers to review both the instructional materials (simulations and assembled worksheets) and the pre- and posttests, and they all confirmed that the tests were measuring the knowledge to be learned from the instructional materials. Second, in a pilot study, fifteen seventh- and eighth-grade students answered an earlier version of the measures, and we had improved the questions to increase their readability based on students' answers in the pilot study.

We had two reasons to have made the pre- and posttest different. First, our second research goal was to compare three different methods to sequence *macro*, *symbolic* and

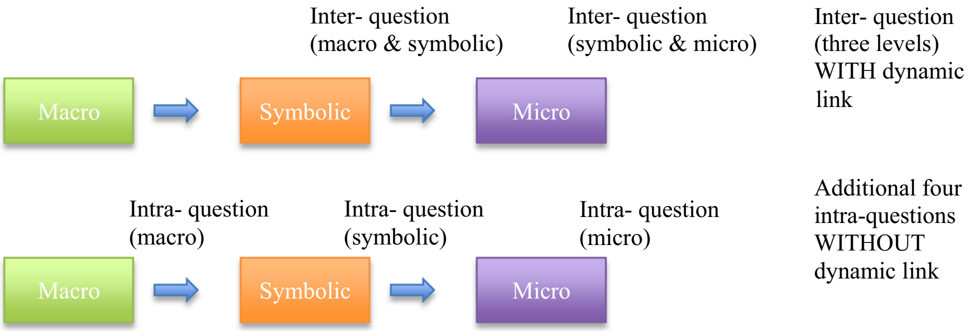


Fig. 4 *Inter-level* scaffolding versus *intra-level* scaffolding in the *macro* first sequence condition. *Note*. Inter- question stands for inter-level question, and Intra- question stands for intra-level question

micro representational activities; therefore, introducing any normative concepts about gas in the pretest might disrupt the manipulation of the sequences. This was the major reason why we only included two questions in the pretest asking participants to explain two gas phenomena without introducing normative concepts such as “gas molecules.” Second, for logistic reasons, the two schools where we conducted our study could only give us two class sessions to complete the experiment; therefore, we had to shorten the pretest to save time for our instruction.

Procedure

This study employed a 2 × 3 factorial design. The study was conducted in a classroom setting over two class sessions on two consecutive days. The total length of the two sessions was around 100 min.

Participants first completed the pretest. Within the same classroom, participants were randomly paired up and assigned to a condition. Two participants in a pair were assigned to the same condition. Each pair shared a laptop with the simulations, but each participant completed the representational activities and answered the scaffolding questions individually in his or her own worksheets. Participants were specifically told to work independently on their worksheets. Three research assistants and the science teacher were present to monitor participants’ learning progress, help them switch to a different simulation page (if needed) and solve technical problems. The research assistants and the science teacher did not provide any content-related instruction. Participants completed the posttest at the end of the second session.

Manipulations

Scaffolding

We created an *inter-level* scaffolding and *intra-level* scaffolding condition by manipulating the scaffolding questions in the assembled worksheets and the dynamic link function in the simulation-based environment.

For the *inter-level* scaffolding condition, we used two scaffolding techniques: three inter-level questions and the dynamic link function. The procedure participants experienced in this condition is as follows:

1. Participants answered the first two inter-level questions (the first and second question in the left column of Table 1), one delivered after the second representational activity and the other after the third representational activity. The order of the two inter-level questions depended on the sequence condition (to be explained in the next subsection). When students were engaging in the representational activities and answering the first two inter-level questions, the dynamic link function was turned off, and students could go to either simulation by clicking a button.
2. Toward the end of the learning session, participants answered the third inter-level question that linked the macro-, symbolic and micro-level (the third question in the left column of Table 1). At this time, the dynamic link function was turned on; thus, participants were able to view the two simulations changing simultaneously (see Fig. 3).

The upper part of Fig. 4 illustrates when the three inter-level questions were delivered in a learning sequence.

For the *intra-level* scaffolding condition, participants answered seven intra-level questions. The dynamic link function was turned off for the entire learning session, and participants could go to either simulation by clicking a button.

1. Participants answered the first three intra-level questions delivered after each representational activity (the first three questions in the right column of Table 1). The place where an intra-level question was inserted depended on the sequence condition.
2. Toward the end of the learning session, participants answered four additional intra-level questions (last four questions in the right column of Table 1) to summarize what they had learned from each representational activity. The lower part of Fig. 4 illustrates when the intra-level questions were delivered in a learning sequence.

Table 2 Mean scores of the six treatment groups in the pretest and posttest

	Inter-level scaffolding			Intra-level scaffolding		
	Macro first Mean (SD)	Micro first Mean (SD)	Symbolic first Mean (SD)	Macro first Mean (SD)	Micro first Mean (SD)	Symbolic first Mean (SD)
Pretest	1.33 (0.65)	1.45 (1.07)	1.16 (0.90)	1.20 (0.88)	1.46 (1.05)	1.32 (0.85)
Posttest comprehension	10.02 (1.93)	8.84 (2.24)	8.70 (3.37)	8.95 (1.89)	7.72 (2.94)	7.76 (2.90)
Posttest application	1.95 (1.15)	2.97 (1.72)	1.80 (1.46)	1.85 (1.56)	1.85 (1.22)	1.63 (1.30)

Note "Macro first" stands for macro-symbolic-micro sequence, "Micro first" stands for micro-symbolic-macro sequence, and "Symbolic first" stands for "symbolic-micro–macro" sequence

The Sequence of Representational Activities

We manipulated the delivery order of the three representational activities in the assembled worksheets to create three sequence conditions: macro-symbolic-micro, micro-symbolic-macro and symbolic-micro–macro. For simplicity, in the results section and discussion section, we refer to the three conditions as *the macro first* sequence, *micro first* sequence and *symbolic first* sequence. The two simulations also differed in their order of display for different sequence conditions. For example, the *macro first* condition viewed the "aerosol can" simulation first, while the *micro first* and *symbolic first* condition viewed the "container of molecules" simulation first.

Coding and Scoring Scheme

The majority of the questions in the pre- and posttest required open-ended responses. For coding and scoring participants' open-ended responses, we developed a coding scheme based on the Structure-Behavior-Function framework. The Structure-Behavior-Function framework has been proved a valid tool to evaluate students' knowledge about a system (Hmelo-Silver et al. 2007). Structural information refers to elements of a system, behavioral information refers to the mechanism of how elements act and interact, and functional information refers to the roles of elements or the outcomes caused by elements' behaviors (Hmelo-Silver and Pfeffer 2004). After reading all participants' responses, the first author developed an exhaustive list of structural knowledge units, behavioral knowledge units and functional knowledge units related to the lesson content participants could possibly provide in their responses. Participants' responses to each question were coded based on the presence/absence of each knowledge unit in this list. The detailed coding scheme and examples could be found in Appendix 3.

Two raters blind to conditions independently coded participants' responses to the open-ended questions, and we achieved high inter-rater reliability. For the pretest, the agreement between the two raters was 98.4 %, Cohen's Kappa = 0.93. For the posttest, the agreement between the two raters was 95.1 %, Cohen's Kappa = 0.89. The two raters resolved disagreement via discussion.

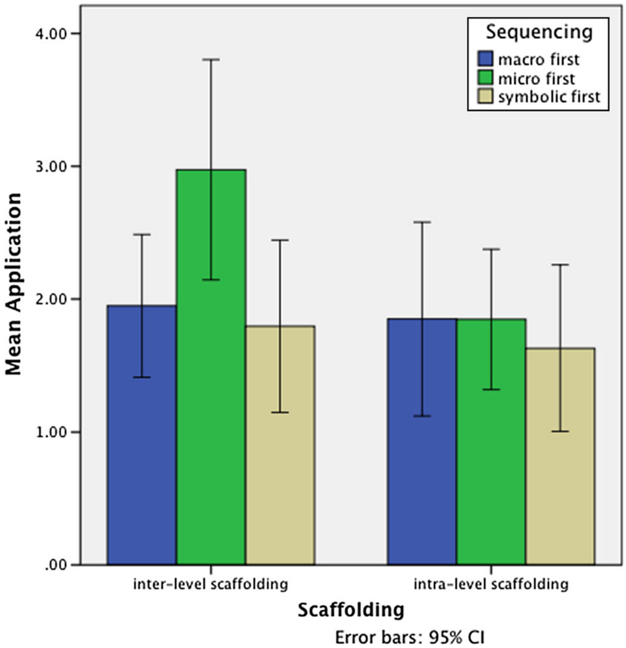


Fig. 5 Mean scores of the six treatment groups in the application test

Behavioral and functional knowledge are more important and difficult than structural knowledge in learning a system (Hmelo-Silver and Pfeffer 2004), and a behavioral and functional knowledge unit contains a structural component. Therefore, we assigned each functional and behavioral knowledge unit with a score of 1 point and assigned each structural knowledge unit a score of 0.5 point.

For the filling-in-blank questions and multiple-choice questions, we assigned 0.5 point to a correct answer and assigned 0 to an incorrect answer. The labeling task in the posttest required participants to label the three variables (i.e., temperature, pressure, volume) and the unit names for the three variables (i.e., k, atm, and l) in a picture. We assigned 1 if a participant correctly labeled all three variables correctly, and assigned 0 if a participant incorrectly labeled one or more variables. We assigned another 1 point if a participant correctly labeled unit names for all variables; similar, we assigned 0 if a participant labeled one or more unit names incorrectly.

Results

Pretest

The first row of Table 2 shows the mean scores of the six treatment groups in the pretest. Pretest scores did not significantly differ across the two scaffolding conditions: $F(2, 117) = 0.674$, $p = 0.512$, nor differed across the three sequence conditions, $F(1, 117) = 0.007$, $p = 0.935$. No interaction between the scaffolding and sequence variable was found either, $F(2, 117) = 0.238$, $p = 0.789$. Equivalency across the six treatment groups was established. Pretest scores were used as a covariate in comparing the posttest scores.

Posttest

Comprehension Test Scores

The second row of Table 2 shows the mean comprehension test scores of each group. The pretest scores were significantly correlated with the comprehension test scores, $F(1, 116) = 9.53$, $p = 0.003$, $\eta^2 = 0.076$. The interaction between the scaffolding variable and the sequence variable was not significant, $F(2, 116) = 0.01$, $p = 0.99$, $\eta^2 < 0.001$. After controlling the pretest scores, the *inter-level* scaffolding showed significant positive effects on the comprehension test compared to the *intra-level* scaffolding condition: $F(1, 116) = 5.31$, $p = 0.023$, $\eta^2 = 0.044$. This result demonstrates that the *inter-level* scaffolding benefits remembering and understanding of the factual knowledge more than the *intra-level* scaffolding.

After controlling the pretest scores, the difference across the three sequence conditions was also statistically significant, $F(2, 116) = 3.53$, $p = 0.033$, $\eta^2 = 0.057$. Pairwise comparisons with Bonferroni error rate adjustment showed that the *macro first* sequence produced marginally higher comprehension test scores compared to the *micro first* condition, $p = 0.053$, and there was a statistical trend that the *macro first* sequence had higher comprehension test scores compared to the *symbolic first* sequence, $p = 0.093$. This result indicates that the *macro first* sequence benefits remembering and understanding of the factual knowledge more than the other two sequences.

Application Test Scores

The application test included the same questions as the pretest. Across all conditions, a paired t test showed significant improvement from the pretest to the application test, $t(122) = 5.7$, $p < 0.001$. The third row of Table 2 presents the mean application test scores of the six treatment groups. Pretest scores were significantly correlated with the application test scores, $F(1, 116) = 27.7$, $p < 0.001$, $\eta^2 = 0.193$. The interaction between the scaffolding variable and the sequence variable was not statistically significant, $F(1, 116) = 2.175$, $p = 0.118$, $\eta^2 = 0.036$. After controlling the pretest scores, the *inter-level* scaffolding showed significant positive effects on application scores, $F(1, 116) = 4.22$, $p = 0.042$, $\eta^2 = 0.035$. This indicates the *inter-level* scaffolding had more positive effects on deep learning than the *intra-level* scaffolding. After controlling the pretest scores, the overall effects of the sequence variable was not significant, $F(2, 116) = 2.02$, $p = 0.137$, $\eta^2 = 0.034$. Although the interaction between the scaffolding and the sequence variable was not significant, the data pattern showed a salient trend that the treatment group that experienced the *micro first* sequence and the *inter-level* scaffolding outperformed the other treatment groups (see Fig. 5). This suggests that given sufficient scaffolding, analyzing a primitive model (i.e., how molecules behave) before learning an aggregate model (i.e., temperature–pressure relationship) might support deep learning. The possible reason for the lack of significance could be that only two application questions were not sensitive enough.

Some Qualitative Observational Data

Although we did not have systematic quantitative data of participants' behaviors in the learning session, our qualitative observations indicated that multiple techniques might have together supported inter-level connection-making across different representational activities. We found that the inter-level questions often initiated connection-making; participants in the *inter-level* scaffolding condition often started to compare the two simulations after they read an inter-level question. In the *intra-level* scaffolding condition in which participants answered intra-level questions, these behaviors were less frequent. Our qualitative observations also suggested that the design technique of structural–functional mapping of simulations might have reduced the extraneous cognitive load for connection-making. Participants in our study did not experience too much difficulty in noticing the connections between the two simulations; for example, when they manipulated the "fire" icon at the bottom of the "aerosol can" simulation, it was easy for them to understand it was the same as manipulating the "temperature" slider in the "container of molecules" simulation. For the *inter-level* scaffolding condition, after reading the third inter-level question that linked the *macro*-, *symbolic* and *micro*-level, participants often began to manipulate one simulation to view the other simulation (the dynamic link was turned on at this time). This was the time when participants were often observed in “aha” and “I see” moments.

Discussion

This study focused on scaffolding in teaching chemistry with graphical simulations, using the ideal gas law as an example topic. The major result was that the *inter-level* scaffolding condition that answered inter-level questions and experienced dynamically linked simulations produced better performance in both the comprehension and application test, compared to the *intra-level* scaffolding condition that answered intra-level questions and did not experience the dynamic link function.

In this study, we tested the effects of the combination of two inter-level scaffolding techniques: (1) inter-level questions and (2) dynamic link of simulations. The manipulation of the scaffolding variable was minimal. Two sets of questions (i.e., inter-level questions vs. intra-level questions) contained a similar amount of information and both required self-explanations. The only difference was that an inter-level question explicitly asked participants to use one level to explain another level, while an intra-level question did not. The dynamic link function was used for only one inter-level question. Such a small manipulation produced significant positive effects on both comprehension and application of knowledge. This indicates the importance of *inter-level* scaffolding for learning multiple representations of chemistry. Furthermore, this result is important because it proves that an effective inter-level question can be as simple as prompting students to use knowledge of one level to explain another level without extra explanatory information.

Why did the *inter-level* scaffolding condition produce better learning than the *intra-level* scaffolding condition? Scientific understanding of the ideal gas law concepts not only required participants to comprehend the particulate nature of gas but also be able to refer to the molecular behaviors to explain abstract macro-level concepts such as “gas pressure” and everyday gas phenomena. Participants learned different levels of knowledge sequentially in three representational activities. The inter-level questions inserted among the representational activities explicitly prompted participants to explain the temperature–pressure relationship and the “aerosol can” phenomenon using their knowledge of gas molecules. This encouraged participants to elaborate their explanations and practice molecular reasoning. In addition, the dynamic link function allowed participants to view the “gas container simulation” and “aerosol can” simulation changing simultaneously, therefore, facilitated connection-making across levels when they were answering the third inter-level question. For the *intra-level* scaffolding condition, although participants received the same amount of information, the intra-level questions inserted among the representational activities only required them to explain knowledge of each level without explicitly asking them to make connections across levels. Therefore, participants were likely to summarize what they learned in each representational activity but were less likely to elaborate their explanations or practice molecular reasoning compared to the participants in the *inter-level* scaffolding condition.

The technology-embedded scientific inquiry (TESI) framework suggests that different tools and techniques could be flexibly integrated into a scientific inquiry model for better knowledge construction because the benefits on learning should be attributed to the learning model rather than any particular tool or technique (Çalik 2013; Ultay and Çalik 2016). Our qualitative observation in this study suggested that several techniques might have together supported connection-making across multi-level chemistry knowledge, including the inter-level questions, the dynamic link of two simulations and the structural–functional mapping of two simulations. It is important to notice that these techniques, either technology realized or non-technology realized, were combined to serve the purpose of *inter-level* scaffolding and facilitating knowledge construction. For future research, it is important to identify different inter-level scaffolding techniques in different learning environments and test the effects of their combinations.

Learning chemistry topics usually involves completing representational activities with a variety of external representations, questions and tasks. Since *inter-level* scaffolding is an important construct that benefits learning multi-level chemistry knowledge, in everyday instruction, teachers can implement a variety of techniques flexibly by keeping in mind that the goal is to help students make connections across different levels of knowledge. For example, in teaching ideal gas law concepts, a typical *macro* activity might ask students to observe and discuss questions such as “why does a car tire become flatter on a cold winter day,” a typical *micro* activity might require students to manipulate a simulation or analyze some static pictures to explore, clarify and explain molecular behaviors. A typical *symbolic* activity may require students to learn or generate line diagrams to represent abstract temperature–pressure–volume relationships, and solve mathematical problems by applying the ideal gas law equation. As students enact these representational activities sequentially, teachers can deliver inter-level questions and tasks in between the activities to emphasize connection-making. For example, after students have completed a few *macro* and *micro* activities, a teacher may ask students to draw gas molecular behaviors in a car tire when it is hot and when it is cold and explain the reasoning for their drawings (macro–micro connection). After students have graphed the temperature–pressure relationship, the teacher can ask students to compare molecular behaviors under different temperatures and explain how different molecular behaviors correspond to different data points in the temperature–pressure graph (micro-symbolic connection).

The second result of this study is that the sequence of representational activities did make a difference in participants' performance in learning a chemistry topic. The *macro first* sequence produced better performance in the comprehension test compared to the *symbolic first* and *micro first* sequence. The *macro first* sequence followed the "concrete to abstract" principle since it allowed participants to gain some experience of a concrete phenomenon before learning the abstract symbolic-level knowledge. This sequence also provided a coherent function-oriented structure for information integration (Liu and Hmelo-Silver 2009). Experiencing a macro-level phenomenon might have clarified the learning goal (i.e., to explain the function why the aerosol can explodes) and have encouraged participants to integrate knowledge to construct a coherent explanation for the phenomenon.

There was a trend that the *micro first* sequence produced better knowledge application performance when participants also received *inter-level* scaffolding. In the *micro first* sequence, participants analyzed molecular behaviors with a concrete graphical simulation before generating abstract representations for the symbolic-level knowledge; therefore, this sequence also followed the "concrete to abstract" principle. Deriving an aggregated macro model (temperature–pressure relationship) after analyzing a primitive micro model (molecular behaviors) might potentially help students construct the conceptual linkage between two levels of knowledge (Frederiksen et al. 1999). However, if not explicitly prompted to make connections, students may not benefit from this sequence.

We do not attempt to make strong conclusions about the sequence variable because participants only completed three representational activities in a short session in this study. However, one important implication of this study is that different sequences might affect the integration of factual knowledge and deep learning differently. Future research may also study how varied sequences can be used to help students construct more flexible mental models on the long run. For example, at an early learning stage, the learning objective can be to construct a coherent explanation of a phenomenon, and students can first experience macro-level phenomena before learning symbolic- and micro-level knowledge. At a later learning stage, the learning objective can be to conceptually understand an abstract aggregate model for problem solving; students can analyze micro-level dynamics with a simulation to derive symbolic-mathematical representations of an aggregate model. To sum up, more research is needed to provide answers to the question of how to sequence representational activities for chemistry learning.

Limitations

This study had several limitations. First, we used measures developed by ourselves and did not use test items in the literature with established validity and reliability. Although we tried best to increase the face validity and readability of our measures, we lacked information to demonstrate the construct validity and internal consistency reliability. Second, the application test only included two questions. Third, our intervention only lasted for two class sessions. Fourth, our sample sizes for cells were relatively small. The small number of test items, short intervention and small sample size might have led to potential lack of statistical power.

Appendix 1: Sample Questions/Tasks in the Three Representational Activities

Questions in the *Macro* Activity

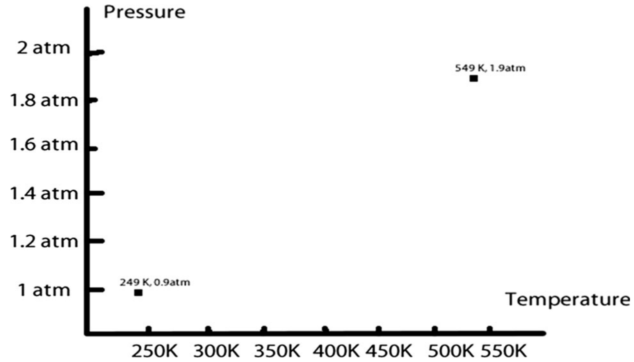
- Slowly drag the fire holder to the bottom of the aerosol can, observe and describe what happens.
- Think about this: Why does the aerosol can explode as you move the fire close enough?

Questions/Tasks in the *Symbolic* Activity

- Slowly drag the temperature slider from left to right, record the values for temperature, pressure and volume for five times.

Temperature	Pressure	Volume

- Please put the data points you recorded in the following graph



- Discuss with your group partners: What do you learn from the data?

Sample Questions in the *Micro* Activity

- Please look at one molecule. Does it move in a certain direction or in random directions?
- How could a molecule keep changing directions?
- Please drag the temperature slider back and forth, describe how do the gas molecules behave and interact with each other?

Appendix 2: Pre- and Posttest

Pretest

1. An infected tooth forms a tiny space that fills with gas. The gas puts pressure on the nerve of the tooth, causing a toothache. Which of the following should the patient choose to relieve pain?

A. Moist heat

B. Ice pack

Why? Explain

2. Car tires are more likely to pop in the summer than in the winter. Please explain why that happens

Posttest

Comprehension subtest

1. Gas is composed of______________
2. Do gas molecules move in certain directions? How do gas molecules behave? How do gas molecules interact with each other?
3. Label the variables on the picture (In this labeling question, a snapshot of the simulation was given, and participants were expected to correctly label temperature, volume and pressure, and the three unit names for the variables)
4. You throw an aerosol can into the fire and it explodes. Please explain how that happens.
5. What is gas pressure? How do you understand gas pressure?
6. When the volume of a certain amount gas stays the same, the higher the temperature, the ______________ the gas pressure. How does that happen?
7. If you want to decrease gas pressure, what should you do? Why?

Application subtest (same as the pretest)

1. An infected tooth forms a tiny space that fills with gas. The gas puts pressure on the nerve of the tooth, causing a toothache. Which of the following should the patient choose to relieve pain?

A. Moist heat

B. Ice pack

Why? Explain.

2. Car tires are more likely to pop in the summer than in the winter. Please explain why that happens.

Appendix 3: Coding and Scoring Scheme and Coding and Scoring Examples (Open-Ended Questions)

Knowledge Units in the Coding Scheme

Functional Knowledge Units

F1	Causal relationship between gas pressure and some macro-level phenomena, e.g., increased pressure caused the car tire to explode
F2	Causal relationship between temperature and pressure, e.g., lower temperature leads to lower pressure
F3	Causal relationship between temperature and speed of molecular movement, e.g., when temperature is higher, molecules move faster
F4	Causal relationship between temperature and molecular collision rate, e.g., when temperature is higher, molecules bounce off more
F5	Causal relationship between molecular behaviors and pressure as an emergent function, e.g., molecules bouncing off more causes pressure to increase

Behavior Knowledge Units

B1	Random movement of gas molecules, e.g., molecules move in random directions, molecules move all over the place
B2	Speed change of gas molecules, e.g., molecules move faster/slower
B3	Bouncing behaviors of gas molecules, e.g., molecules collide with each other, and molecules bounce off container walls

Structural Knowledge Units

S1 Mention “temperature” of gas without mentioning its relationship to gas pressure or molecular behaviors, e.g., it is about temperature

S2 Mention “molecules” without describing their behaviors or interactions, e.g., because of molecules

Coding and scoring procedure In order to increase the objectivity in scoring participants’ answers, we reviewed each answer to an open-ended question for the presence and absence of each knowledge unit listed above. We applied the codes F1, F2, F3, F4, F5, B1, B2, B3, S1, S2 if the associated knowledge units were present. To score an answer, we assigned 1 point to each functional and behavior knowledge unit and assigned 0.5 point to each structural knowledge unit. If an answer did not contain any of the knowledge units in our list, no code was assigned and the answer was scored 0.

Sample question from the comprehension subtest: Do gas molecules move in certain directions? How do gas molecules behave? How do gas molecules interact with each other?	Sample question from the comprehension subtest: You throw an aerosol can into the fire and it explodes. Please explain how that happens	Sample question from the comprehension subtest: What is gas pressure? How do you understand gas pressure?	Sample question from the application subtest: Car tires are more likely to pop in the summer than in the winter. Please explain why that happens
Answer: “By behaving, I think” Code: none Score: 0	Answer: “It happens by the can burning up as the fire moves closer to the aerosol can” Code: none Score: 0	Answer: “Gas pressure is when you pressure the gas” Code: none Score: 0	Answer: “Because the sun makes it explode” Code: none Score: 0
Answer: “Bumping into each other” Code: B3 Score: 1	Answer: “Heat in the fire makes molecules in the can go crazy then end up exploding” Code: F3 Score: 1	Answer: “Gas pressure is made of molecules, I don’t know the rest” Code: S2 Score: 0.5	Answer: “They are more likely to pop in the summer because the heat of the sun would make the tire to get heated up and over inflate” Code: S1 Score: 0.5
Answer: “Gas molecules go random ways, gas molecules interact with each other by bumping into each other” Code: B1, B3 Score: 2	Answer: That happens because the more something heats up the faster the molecules move so they hit the walls of the soda cans so hard and much the can exploded Code: F3, F4 Score: 2	Answer: “Gas pressure is when the pressure in the air is heavy so the molecules movement are at full speed” Code: B2 Score: 1	Answer: “In the summer would pop the tires, because of the temperature, if it’s hot the pressure will rise” Code: F2 Score: 1
Answer: They move in random directions and they bounce off each other. They move fast and slow Code: B1, B3, B2 Score: 3	Answer: “The molecules create an impact by bumping into each other when in contact with heat, therefore creating pressure that the can can’t hold” Code: F3, F2, F5 Score: 3	Answer: “What I know about gas pressure is that if the temperature is high the molecules moved faster, the pressure controlled the molecules” Code: F2, S2 Score: 1.5	Answer: “Because of the molecules speeding and there is a lot of pressure on the tires so they pop” Code: B2, F1 Score: 2

Overall number and proportion of students who scored 0–0.5 (low-level understanding—LU), 1–1.5 (medium-level understanding—MU) and > 1.5 (high-level understanding—HU) for each item

LU	MU	HU	LU	MU	HU	LU	MU	HU	LU	MU	HU
$N = 8$	$N = 36$	$N = 79$	$N = 64$	$N = 37$	$N = 22$	$N = 96$	$N = 27$	$N = 0$	$N = 69$	$N = 28$	$N = 26$
7 %	29 %	64 %	52 %	30 %	18 %	78 %	22 %	0 %	56 %	23 %	21 %

Note To demonstrate how well students answered the open-ended questions in general, we selected four open-ended questions from the posttest and calculated the overall number and proportion of students who demonstrated low-level understanding, medium-level understanding and high-level understanding. In the results section, for statistical comparisons across the six conditions, we summed up the scores of all questions in the pre- and posttest for each student and compared group means of overall scores

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