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Asymmetric translation between multiple representations in chemistry

Yulan I. Lin[a], Ji Y. Son[b] and James A. Rudd II[a]

[a]Department of Chemistry & Biochemistry, California State University, Los Angeles, CA, USA; [b]Department of Psychology, California State University, Los Angeles, CA, USA

ABSTRACT

Experts are more proficient in manipulating and translating between multiple representations (MRs) of a given concept than novices. Studies have shown that instruction using MR can increase student understanding of MR, and one model for MR instruction in chemistry is the chemistry triplet proposed by Johnstone. Concreteness fading theory suggests that presenting concrete representations before abstract representations can increase the effectiveness of MR instruction; however, little work has been conducted on varying the order of different representations during instruction and the role of concreteness in assessment. In this study, we investigated the application of concreteness fading to MR instruction and assessment in teaching chemistry. In two experiments, undergraduate students in either introductory psychology courses or general chemistry courses were given MR instruction on phase changes using different orders of presentation and MR assessment questions based on the representations in the chemistry triplet. Our findings indicate that the order of presentation based on levels of concreteness in MR chemistry instruction is less important than implementation of comprehensive MR assessments. Even after MR instruction, students display an asymmetric understanding of the chemical phenomenon on the MR assessments. Greater emphasis on MR assessments may be an important component in MR instruction that effectively moves novices toward more expert MR understanding.

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Science education; multiple representations; chemistry education; concreteness fading; assessment

Introduction

Multiple representations

The ability to link information and ideas across multiple representations (MRs) for a given concept is a more meaningful indicator of understanding than manipulation of symbolic notation (Ainsworth, 1999; Prain, Tytler, & Peterson, 2009; Prain & Waldrip, 2006; Treagust, Chittleborough, & Mamiala, 2003). For example, many chemistry students can learn to balance reaction equations, but providing correct coefficients and chemical symbols for equations is not the same as understanding the molecular behavior or macroscale phenomena represented by the equations (Gabel, Samuel, & Hunn, 1987; Yarroch,

CONTACT James A. Rudd II jrudd@calstatela.edu Department of Chemistry & Biochemistry, California State University, 5151 State University Drive, Los Angeles, CA 90032, USA

1985). The importance of MR understanding is also true of other fields, including physics, math, and biology (Hmelo-Silver, Marathe, & Liu, 2007; Kohl & Finkelstein, 2008; Kohl, Rosengrant, & Finkelstein, 2007; McNeil & Fyfe, 2012; Schnotz & Kulhavy, 1994; Tsui & Treagust, 2013). Previous work in MR has investigated expert use of MR (Chi, Feltovich, & Glaser, 1981; Kozma & Russell, 1997; Larkin, McDermott, Simon, & Simon, 1980), student understanding of MR, and the use of MR in instruction (Bibby & Payne, 1993; Dienes, 1973; Hennessy et al., 1995; Kaput, 1989; Oliver, 1997; Schwartz, 1995; Tabachneck, Koedinger, & Nathan, 1994; Thompson, 1992).

Experts are better at manipulating and translating between MRs than novices. They tend to represent underlying function and behavior in their models, while novices base their models on surface features of appearance and structure (Chi et al., 1981; Hmelo-Silver et al., 2007; Kozma & Russell, 1997; Larkin et al., 1980). Chemistry experts connect MR that are conceptually related more efficiently and accurately than novices (Kozma, 2003). Physics graduate students translate between MR during problem-solving more easily than physics undergraduate students (Kohl & Finkelstein, 2008). Even in domains outside of the natural sciences (e.g. economics), experts reason by seamlessly transitioning between MR (Larkin & Simon, 1987).

Unlike experts, novices generally find working with MR difficult. Studies assessing MR understanding have demonstrated that students are worse at problems that require them to translate between different representations than single-representation problems (Ainsworth, Wood, & Bibby, 1996, 1998; Ramnarain & Joseph, 2012; Tabachneck, Leonardo, & Simon, 1994; Yerushalmy, 1991). However, there has been little work to address what types of MR problems may be more difficult than others. It is commonly assumed that deficiencies in MR understanding may be traced back to instructional practices: not all representations are given the same weight in instruction. For example, there may be an overpresentation of one particular representation type in instruction or it may be more common to ask students to translate from one representation to another than vice versa (e.g. typically students are asked to provide a graph from equation than the other way around, Dugdale, 1982). There have been many attempts to improve MR translations through innovative pedagogy (e.g. Hennessy et al., 1995; Kozma, Chin, Russell, & Marx, 2000; Thompson, 1992).

Given the centrality of MR in expert-like thinking, each knowledge domain should consider which MR to include in instruction. One model for MR in chemistry instruction is the chemistry triplet, first proposed by Johnstone (1982) and consisting of three representations: the macroscale, the nanoscale (also referred to as the 'micro' or the 'sub-micro'), and the symbolic (Figure 1) (Johnstone, 2000a, 2000b, 2009).

The macroscale representation is at the human scale in which natural phenomena can be observed through the senses (sight, touch, etc.). The nanoscale representation is at the molecular scale of molecules, atoms, and other particles that cannot be directly observed by human senses. The symbolic representation is the abstract representation of natural phenomena through the use of symbols, equations, and so on. The chemistry triplet is often shown as the corners of an equilateral triangle to symbolize the equal importance of each type of representation and the links between them in understanding chemistry. The edges of the triangle represent possible translations among the three representations.

Although this interpretation of the triplet is common, other valid frameworks and perspectives exist and are in use in chemistry education research and instruction (Gilbert &

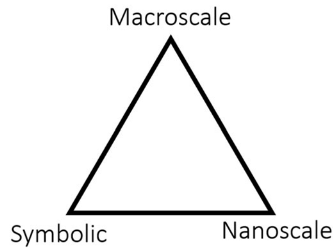

Figure 1. The chemistry triplet
Source: Adapted from Johnstone (1982).

Treagust, 2009a; Taber, 2013; Talanquer, 2011). Thus, implementation of the triplet model, whether for research or instruction, requires clear identification of the triplet and the aspects that are being emphasized. To provide clarity before proceeding further, our implementation attempts to hold closely to Johnstone's views of the macroscale, nanoscale (submicro), and symbolic. Our view of the macroscale emphasizes the actual physical phenomena experienced tangibly through human senses, rather than a macroscale property or conceptual framework such as density or pH. Our view of the nanoscale emphasizes ball-and-stick and space-filling models as descriptive, explanatory, and predictive representations of the nanoscale, rather than as mere symbolic icons (Talanquer, 2011). Lastly, our view of the symbolic emphasizes that the symbols, formulas, equations, and so on, span the macroscale and nanoscale (Taber, 2013), for example, $H_2O(s)$ symbolizes both the macroscale ice and the nanoscale collection of water molecules vibrating closely together in fixed positions in an ordered structure.

Perhaps due in part to the potential for ambiguity in interpretations of the triplet, chemistry novices (students) are far less skilled than chemistry experts at translating between the corners of the triplet and understanding the underlying concepts that tie the different representations together. Not only do chemistry students correctly balance equations without understanding the meaning of the equations (Gabel et al., 1987), they are most comfortable manipulating symbols and symbolic representations using flawed algorithms, rather than considering underlying concepts (Gabel, 1993; Gabel et al., 1987; Nurrenbern & Pickering, 1987; Nyachwaya, Warfa, Roehrig, & Schneider, 2014; Smith & Metz, 1996). Students also misunderstand the relationship between macroscale properties and nanoscale processes (Griffiths & Preston, 1992; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993). For example, some students assume that an atom isolated from a gas will embody the bulk properties the gas exhibits on the macroscale, just on a smaller scale (Ben-Zvi, Eylon, & Silbemein, 1986). A study of student performance on a standardized chemistry exam revealed that South African 12th graders performed worse on questions that require translation between MR than on questions that do not require translation (Ramnarain & Joseph, 2012).

Student proficiency in manipulating symbols without understanding the underlying meaning and their discomfort in translating across MR may be a result of chemistry instruction that concentrates on symbolic representations. Unsurprisingly, instruction that explicitly teaches MR has been shown to strengthen student understanding of MR and increase their ability to translate between the different corners of the chemistry triplet (Gabel, 1993). In one study, tenth-grade Lebanese students who were explicitly taught the different corners and the relationships between corners performed significantly better on a concept map task than students who did not receive the MR instruction (Jaber & BouJaoude, 2012). In a study of eighth-grade Greek students who were taught macroscale representations first, then symbolic, and then nanoscale performed better on postassessments and retained more information (Georgiadou & Tsaparlis, 2000). Even in domains outside of chemistry, explicitly teaching MR has been found to improve student understanding of MR (Kohl et al., 2007; Tsui & Treagust, 2013).

Although MR instruction in science appears to be more effective than single-representation instruction, less work has been done identifying what types of MR translations are most difficult for students and whether MR instruction can alleviate those difficulties. Translations between different corners of the chemistry triplet may vary in difficulty depending on the corners involved and the direction of translation. In other words, there may be an asymmetry in students' ability to move between different representations. As a theoretical framework for investigating these issues, we look to the research on the benefits of concrete and abstract representations in the learning sciences.

Concreteness fading: combining learning benefits of concrete and abstract representations

There have been many empirical investigations regarding the role of concrete and abstract representations in advancing conceptual and generalizable understanding. Concrete representations are connected to their referents through perceptual similarity and are often linked to learners' prior experience. For instance, a concrete representation of melting could be a video of ice melting in a glass. In contrast, abstract materials are more arbitrarily associated with referents and are perceptually stripped down in form. A chemical equation represents melting in an abstract way because symbols such as (s) and (l) reference physical states only by convention. Studies in cognition have demonstrated two principles: (1) instruction with MR generally leads to more robust understanding than with a single representation (e.g. Brenner et al., 1997; Gentner & Markman, 1997) and (2) presenting the most concrete instantiation first then presenting abstract materials, known as concreteness fading, leads to better generalization (see Fyfe, McNeil, Son, & Goldstone, 2014 for a recent review). University students in the USA who received instruction about complex systems with concrete-then-abstract representations performed better on a transfer test than students who either received abstract-to-concrete instruction, abstract representations only, or concrete representations only (Goldstone & Son, 2005). Another study examined concreteness fading instruction in the context of learning algebra and found that undergraduates who received concreteness fading instruction outperformed those who either received abstract-only instruction or concrete-only instruction on delayed tests administered three weeks after initial learning (McNeil & Fyfe, 2012).

The mechanism behind the success of concreteness fading may have to do with maximizing the benefits of concrete and abstract materials (Fyfe et al., 2014). Concrete materials ground a new concept in a familiar or graspable context, while abstract materials limit unnecessary detail, facilitating generalization. Progressing from concrete to abstract examples initially anchors new knowledge in already familiar territory then moves the learner toward a more abstract and transferrable understanding of the concept. A second benefit of progressing monotonically along a concreteness continuum is that it minimizes the cognitive leaps needed to move from one example to the next (Freudenthal, 1983; Kotovsky & Gentner, 1996). For instance, moving from a macroscale representation to a nanoscale representation may be more accessible than moving all the way from a macroscale representation to a symbolic representation.

Concreteness fading and MR assessment

Much of the research on concreteness fading has focused on the presentation of MR to novice learners (Fyfe et al., 2014). Only a few studies have examined concreteness in assessment, and these studies contrast assessments utilizing concrete materials with assessments utilizing abstract materials (e.g. Petersen & McNeil, 2013). Very little research has focused on the design and implementation of assessing students' ability to connect and translate across concrete and abstract MR. One study on pattern perception in preschool-aged children found that the direction of assessment, in this case an abstract cue with concrete answer choices versus a concrete and perceptually rich cue with abstract answer choices, can affect generalization (Son, Smith, & Goldstone, 2011). Research on the direction of assessment is critical because the way in which we query students defines the scope of understanding that students can demonstrate. A student might appear quite competent on one type of assessment but not be able to demonstrate their understanding on a different type of assessment. Thus, in considering how to measure student understanding of MR, we need assessments that examine connections between MR. An open question is whether science students can translate from concrete to abstract representations as well as they can translate from abstract to concrete.

Concreteness and the chemistry triplet

The concreteness and abstractness of the three corners of the chemistry triplet can be interpreted through different perspectives. Gilbert and Treagust (2009b) raise the issue of relating 'types' of representations to 'levels' of representations that define the cognitive relationship between the types of representations (i.e. the separate corners of the triplet) from the human learner perspective. Level could mean differences in physical scale from macro to meso to nano (submicro), but level could also indicate differences in the language that describes phenomena, such as concrete descriptions of macroscale to abstract chemical symbols. Thus, two psychological dimensions of concreteness may be operating in the chemistry triplet: scale, where the macroscale that is more perceptible to humans could seem more concrete and the less perceptible nanoscale could seem less concrete, and language, where familiar language is more concrete and more specialized language that requires training and education is more abstract. Justi, Gilbert, and Ferreira (2009) identify concrete as one mode of representation used to communicate a person's mental model and indicate that the model can be expressed as a mixture of representation modes (concrete, verbal, etc.) when providing the external representation to the learner (p. 286). This dimension of concreteness in modes of communication allows for representations to be viewed as more or less concrete, for example, a broad qualitative analogy describing a concept may feel more concrete to a learner than a quantitative, mathematical expression of the same concept.

In the work presented in this paper, our goal was to map the corners of the triplet to a single concreteness continuum in order to situate our research within the broader frameworks developed in the cognitive and learning sciences, and we began with the basis that all representations (verbal, pictorial, symbolic, video, gesture, etc.) can be placed on a concreteness continuum. Specifically, we define the concreteness of a representation as similarity to the referent or the intended meaning of the representation. Thus, the macroscale is considered the most concrete of the three corners because macroscale representations, whether they are verbal descriptions or videos of macroscale phenomena, most closely resemble their referents. For example, a video of ice melting more closely resembles the actual observable phenomena of ice melting, and is therefore more concrete than the symbolic representation of ice melting: $H_2O(s) \rightarrow H_2O(l)$.

Symbolic representations, such as chemical symbols, formulas, and equations, are less concrete because they are more arbitrarily connected to the referent. Also, symbolic representations are very reduced representations of the referent, and the relationship between the symbolic representation and the meaning of the representation is more obscured. Specialized training is typically needed in order for a person to succeed in connecting the representation with its meaning. Using 'H' to mean hydrogen simply because hydrogen starts with the letter 'H' is a connection between the symbolic representation and referent that is arbitrary and reliant on conventions in our culture and language. For instance, 'Cu' as the symbolic representation of the substance 'copper' is more arbitrary for English speakers than for French speakers ('cuivre'). In French, the symbolic representation at least resembles the word more closely than in English, but in both languages, the symbols are still more arbitrary than the relationship between a macroscale representation, such as a picture showing a sample of each metal, of these referents.

We place nanoscale representations in between the more concrete macroscale and more abstract symbolic representations. Nanoscale representations are somewhat concrete in that ball-and-stick and space-filling models capture some of the perceptual qualities of the referent of atoms and bonds than the arbitrariness of symbols. However, ball-and-stick nanoscale representations are also less concrete than macroscale representations because nanoscale representations also have elements of arbitrariness, for example, colors are assigned to different elements by convention, such as oxygen atoms are often colored red and the size of the balls distort the actual and relative size of atoms.

Essentially, the more concrete end of our concreteness continuum captures more of the qualities of the referent and requires less specialized training to understand the meaning of the representation, whereas the more abstract end of the continuum has fewer and weaker connections between the representation and the referent and requires more specialized training for learners to interpret the representation. Although this approach is not the only way of describing the concreteness and abstractness of the corners of the chemistry triplet, it allows us to connect to the learning literature research on manipulating concreteness to help students move between concrete and abstract representations.

Concreteness fading and the chemistry triplet

In this study, we investigated the application of concreteness fading to MR instruction and assessment in teaching chemistry. To do this, the chemistry triplet was mapped to a concreteness continuum (Figure 2(a)).

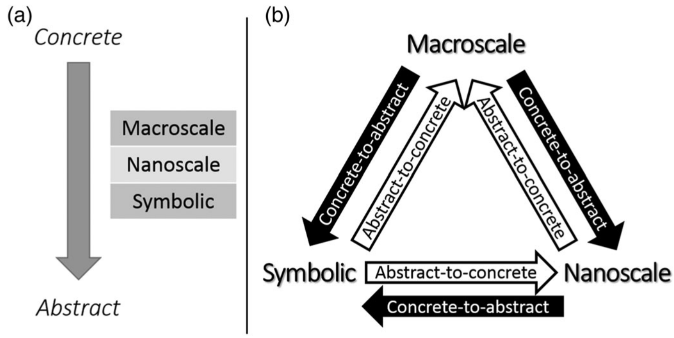

Figure 2. (a) The relationship between the chemistry triplet and concreteness fading. (b) Directionality of transitions between the corners of the chemistry triplet.

For the purposes of this study, the macroscale representation of objects, phenomena, and manipulations is on the human scale (i.e. observed or experienced through sight, hearing, touch, etc.) and is considered the most concrete (Johnstone, 2000a, 2000b, 2009). The nanoscale representation of the molecular level is less concrete because the nanoscale is less perceptually accessible to humans; however, molecules, atoms, and so on can be represented by graphical icons (e.g. pictures of spheres to represent atoms) or physical models (e.g. ball-and-stick models) that provide a perceptual anchor. Lastly, the symbolic representation is the least concrete (most abstract) because chemical symbols and equations reference substances and processes by convention in a highly efficient and simplified manner (Johnstone, 2000a, 2000b; Taber, 2013). Thus, in mapping the chemistry triplet onto a concreteness continuum, we have placed the macroscale and symbolic at the extremes and the nanoscale as intermediate between them.

Because the chemistry triplet is typically shown as an equilateral triangle, there may be an underlying assumption that each representation (corner) and each direction of translation between representations are somehow equal (Figure 2(b)). However, considering a linear concreteness continuum may help us explore the hypothesis that these representations and translations may not be cognitively equivalent for chemistry novices. Although the ideal may be that chemistry students should understand each representation equally well, some translations may initially be easier than others (Figure 2(b)).

If deep understanding of chemistry includes understanding all three corners, how they relate, and how to translate between them, then using a concreteness continuum provides a framework for asking questions about MR instruction and assessment. Should the more or less concrete representation be presented first in MR instruction? Are students equally adept at translating from concrete to more abstract representations or from abstract to more concrete ones? That is, does the direction of translation matter in assessment?

Here, we report new findings on MR instruction and assessment, and our findings shed light on students' ability to translate between representations. Specifically, our investigation addressed the following research questions to examine the role of concreteness in learning MR in the domain of phase changes in chemistry:

(1) Type of first presentation: do students perform better with concrete-first or abstract-first instruction? That is, do students perform better with macroscale instruction first or symbolic instruction first?

(2) Inclusion of a progression: do students perform better with instruction that progresses monotonically along a concreteness continuum vs. instruction that does not include a progression? That is, would students benefit most from macroscale, then nanoscale, then symbolic instruction?
(3) Directionality of assessment: do students perform better on concrete-to-abstract or abstract-to-concrete questions? That is, are students more adept at translating from more concrete to less concrete corners of the chemistry triplet (black arrows in Figure 2(b)) or vice versa (white arrows in Figure 2(b))?

Experiment 1

Students were shown chemistry instructional videos on phase changes in small groups that were randomly assigned to one of four instructional conditions. Each participant completed pen-and-paper pre- and postassessments that contained two types of questions (concrete-to-abstract, abstract-to-concrete).

Methods

Participants

One hundred forty-seven undergraduate students (100 female, 44 male, 3 declined to state) from the Psychology department subject pool (most of whom were enrolled in introductory Psychology courses) at a mid-sized comprehensive public university on the west coast of the USA participated in Experiment 1. Participants were given course credit for being in the study. Twenty additional participants were excluded from analysis because they did not complete the study.

Instruments

Instructional videos

Participants viewed three videos during the instruction, and each video presented phase changes from the perspective of one corner of the chemistry triplet.

The macroscale instructional video introduced the macroscale, showed videos of water freezing and ice melting (obtained from vimeo.com by permission of the owners), and had added voiceover narration that described the melting and freezing of water being shown.

The nanoscale instructional video first introduced the nanoscale, including a brief nanoscale drawing tutorial. Then, the video showed a screencast recording of one of the researchers interacting with the 'States of Matter: Basics' simulation (PhET States of Matter: Basic Simulation, n.d.), which again had added voiceover narration.

The symbolic instructional video introduced symbolic notation, and presented symbolic representations for phase changes and three properties associated with phase changes (velocity, kinetic energy, and temperature). Because velocity, kinetic energy, and temperature were presented to the participants as symbols (i.e. V, KE, T), we considered these to be symbolic representations (although the actual underlying concepts could be interpreted through other perspectives of the triplet, e.g. temperature as a macroscale construct and kinetic energy as a nanoscale concept).

All videos discussed kinetic molecular theory; the relationship between velocity, kinetic energy, and temperature; and the relationship between the energy of the atoms or molecules and the phase or state of matter.

Assessments

Participants completed two-part assessments before and after instruction, which were designed to assess students' ability to translate between the different representations of the chemistry triplet. Each question required students to connect different representations by giving one representation of a concept and asking students to provide a different representation.

In Experiment 1, questions were written to assess two directions of translation: concrete-to-abstract and abstract-to-concrete. Figure 3 shows the relationship between question directionality and the chemistry triplet.

The questions were also designed to assess transfer beyond memorization of presented materials. Though the instruction focused on melting and freezing of water, participants were asked about other substances and states of matter. Two parallel versions of the assessments were created with nearly identical questions. For example, if Assessment A Question 1 asked about a substance melting, then Assessment B Question 1 asked about the same substance freezing. Participants randomly received either Version A of the pretest and posttest or Version B. Sample questions are shown in Table 1.

The pretest and posttest had concrete-to-abstract and abstract-to-concrete translation questions. At the end of the posttest, participants ranked their confidence in their answers, estimated their ability to learn science, and reported how much they liked science.

Experimental design and procedure

The experiment used a pretest, intervention, and posttest procedure and a $2 \times 2 \times 2$ mixed repeated-measures design corresponding to the three research questions. The two between-subjects factors were first presentation (concrete-first, abstract-first) and progression (progression, no progression) (Table 2). The within-subjects factor was question directionality (concrete-to-abstract, abstract-to-concrete).

For the concrete-first, progression condition, the videos were presented in the order macroscale–nanoscale–symbolic (M–N–S). The M–N–S condition is a progression

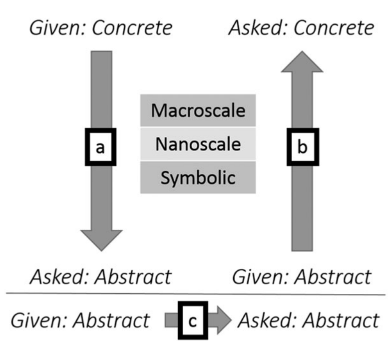

Figure 3. Assessment questions classified by directionality. (a) Concrete-to-abstract; (b) abstract-to-concrete; and (c) abstract-to-abstract.

Table 1. Sample questions classified by direction.

Sample concrete-to-abstract question	Sample abstract-to-concrete question
(*Given macro → provide symbolic*) Given a chunk of solid aluminum, represent it in symbols.	(*Given symbolic → provide nano*) Select the nanoscale picture that most accurately represents a sample with the symbol $H_2O(s)$.
(*Given macro → provide nano*) Draw a nanoscale picture to represent solid aluminum.	(*Given symbolic → provide macro*) Name the physical process represented by the chemical equation $N_2(g) \rightarrow N_2(l)$.
(*Given nano → provide symbolic*) Given a set of nanoscale pictures below, pick out the corresponding chemical equation.	(*Given nano → provide macro*) Name the physical process represented by the nanoscale image below.

Table 2. Four instructional conditions based on first presentation and progression.

	Progression	No progression
Concrete-first	M–N–S	M–S–N
Abstract-first	S–N–M	S–M–N

because the examples progress monotonically along the concreteness continuum from most concrete to most abstract. For the abstract-first, progression condition, the videos were presented in the order symbolic–nanoscale–macroscale (S–N–M). The S–N–M condition is a progression because the examples progress monotonically along the concreteness continuum from most abstract to most concrete. For the concrete-first, no progression condition, the videos were presented in the order macroscale–symbolic–nanoscale (M–S–N). For the abstract-first, no progression condition, the videos were presented in the order symbolic–macroscale–nanoscale (S–M–N). Both M–S–N and S–M–N conditions did not progress monotonically on the concreteness continuum.

Participants signed up for experimental sessions in groups of 10–16 students. Each session was randomly assigned to one of the four presentation conditions. Participants were allotted 11 minutes to complete the pretest and were then shown the instructional videos for 23 minutes. Participants were then given 11 minutes to complete the postassessment. At the end of the posttest, participants completed a brief demographic survey.

Data analysis

Coding

The responses were scored using a rubric for each question and yielded for each participant an overall score, a concrete-to-abstract score, and an abstract-to-concrete score for the pre- and postassessments. For each participant, a gain score was calculated as posttest score minus pretest score.

Responses involving drawn nanoscale images were independently scored by another rater using the same scoring rubric, and discrepancies were resolved by an experienced chemistry professor. This coding was blind to presentation condition.

Statistical analysis

The gain scores were analyzed using a $2 \times 2 \times 2$ mixed repeated-measures ANOVA (question direction × first presentation × progression) with participants' pretest scores as a covariate.

Results and discussion

The ANOVA results revealed that first presentation and progression had no statistically discernable effect ($F < 0.20$, $p > .700$) and no significant interactions ($F < 1.5$, $p > .23$). However, there was a main effect of question directionality ($F(1, 147) = 233.67$, $p < .001$, $\eta^2 = 0.62$). Students improved significantly more on concrete-to-abstract questions than on abstract-to-concrete questions (Figure 4) for all presentation conditions.

Because participant credit was based only on attendance, rather than performance on the postassessment, participants had little incentive to learn the material and perform well on the assessment. To address this limitation, Experiment 2 was designed to include general chemistry students who were motivated to learn the material.

Experiment 2

Two types of students were randomly assigned to one of four instructional conditions (Table 2). Each participant completed an online assignment composed of instructional videos and a postinstructional assessment with three types of questions (concrete-to-abstract, abstract-to-concrete, abstract-only).

Methods

Participants

Two hundred forty-nine undergraduate students enrolled at a mid-sized comprehensive public university on the west coast of the USA participated in the study for course credit. Students from the Psychology department subject pool ($n = 168$; 124 females, 36 males, 8 declined to state) received credit for attendance. Students enrolled in a general chemistry course ($n = 81$; 43 females, 38 males) received credit scaled to their assessment performance. The inclusion of chemistry students enhances the validity of the study results because these students had incentive to learn the material and perform well on the assessment.

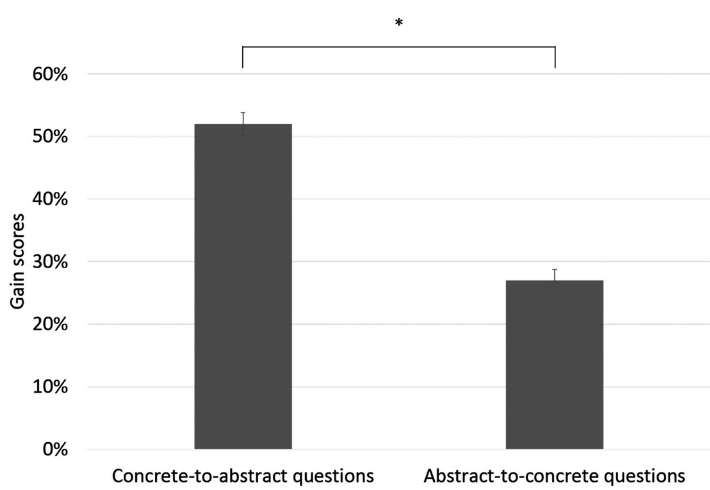

Figure 4. Mean gain scores for the two different types of questions ($n = 146$).

Datasets were excluded from analysis if participants did not complete the study, including those who spent less than 20 minutes on the study because the instructional videos were over 17 minutes in length and the assessment required a minimum of three minutes for one of the researchers to complete.

Instruments

The instructional videos and assessment questions were the same as for Experiment 1, except the questions were slightly modified for online delivery. Also, a third type of assessment question (abstract-to-abstract) was added because most general chemistry tests focus on symbolic understanding and manipulations.

Experimental design and procedure

The experiment used an intervention and posttest procedure and a $2 \times 2 \times 2 \times 3$ mixed repeated-measures design. The pre-assessment was removed to reduce participant time and pretest effects. The between-subjects factors were first presentation (concrete-first, abstract-first), progression (progression, no progression), and student population (psychology students, chemistry students). The within-subjects factor was question directionality (concrete-to-abstract, abstract-to-concrete, abstract-to-abstract).

Participants were randomly assigned to one of the four presentation conditions using Qualtrics software (Provo, UT). The postassessment and demographic survey were also presented on Qualtrics immediately after the instructional videos.

Students from the Psychology department subject pool signed up in groups of 1–20 to participate in a computer lab. Each participant had an individual workstation with headphones and was given 45 minutes to complete the study.

Students enrolled in the general chemistry course received the link to the Qualtrics experiment from their course instructor after the first midterm exam. Students completed the study independently as a homework assignment and were asked to provide their name and instructor name to award them appropriate class credit. Before data analysis, all identifying information was decoupled from the performance data.

Data analysis

Coding

The responses were scored using a rubric for each question and yielded for each participant an overall score, a concrete-to-abstract score, an abstract-to-concrete score, and an abstract-to-abstract score. These raw scores were converted to proportion correct postassessment scores. All coding was blind to presentation condition.

Statistical analysis

The postassessment scores were analyzed using a $2 \times 2 \times 2 \times 3$ mixed repeated-measures ANOVA (first presentation × progression × student population × question direction).

Results and discussion

The ANOVA results showed that first presentation and progression did not have a statistically significant effect ($F\text{s} < 0.1$, $p > .2$); however, there was a statistically significant

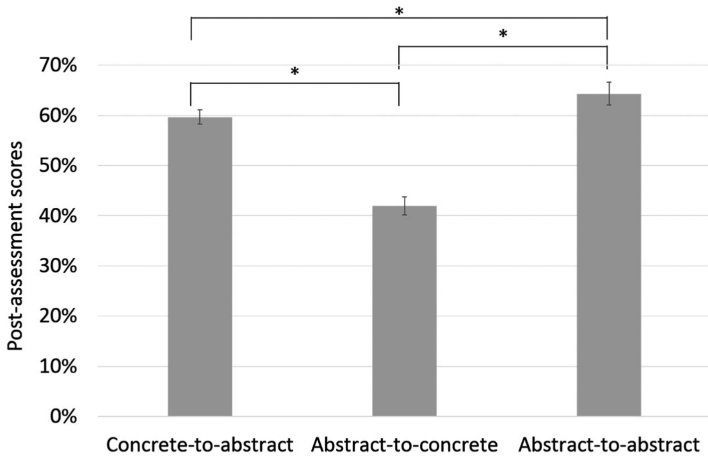

Figure 5. Mean postassessment scores for the two different types of questions ($n = 249$).

effect of student population, $F(1, 241) = 53.01$, $p < .001$, $\eta^2 = 0.24$, and question direction, $F(1, 241) = 74.56$, $p < .001$, $\eta^2 = 0.34$. There were no reliable interactions.

Unsurprisingly, students enrolled in the chemistry course ($M= 0.71$, $SD= 0.20$) performed significantly better than students enrolled in the psychology course ($M= 0.54$, $SD = 0.22$). Post-hoc-corrected simple comparisons revealed that participants performed the best on abstract-to-abstract questions, then concrete-to-abstract questions, and worst on abstract-to-concrete questions (ps < .001). Mean scores on these three question types are shown in Figure 5. The asymmetry in student performance based on question direction that was found in Experiment 1 was confirmed here with a sample of students that had more motivation to learn chemistry and do well on the assessment, and presumably, more initial chemistry knowledge.

Discussion

Taken together, the experiments reveal unexpected findings regarding concreteness and MR chemistry instruction and assessment. First, neither experiment yielded differences in student performance between different instructional conditions. The order of MR instruction, whether starting with most concrete vs. most abstract or including a progression, did not observably impact student performance, meaning that concreteness fading did not appear to have an effect, at least for learning how to translate between MR in chemistry. Although our experimental design did not yield any significant influence of instructional order, it may be that the brief instructional period limited students' ability to gain sufficient understanding of the triplet, and additional research may detect an effect of MR instructional order over longer time periods (e.g. an entire class period or course) and/or with a wider variety of chemistry topics.

Differences in the learning goal between this study and most concreteness fading studies may also explain the absence of any effect. In most concreteness fading studies, the goal is for students to learn to generalize to a new and completely different concrete example of the abstract concept being examined (Goldstone & Son, 2005; McNeil &

Fyfe, 2012). For example, in a typical study, US undergraduates were taught the commutative rule using generic symbols, cups, and pies and were assessed by being asked to generalize to examples with ladybugs, vases, and rings (McNeil & Fyfe, 2012). In this study, however, the goal was for students to understand and translate between MR of the concept, and students were assessed by being asked to translate across MR for new examples of the concept, rather than simply by identifying new instances of the concept. Similarly, another study assessing MR use in chemistry evaluated participants on their ability to translate between videos, graphs, animations, and equations of the same concept (Kozma & Russell, 1997).

When translation is the goal, rather than just identifying examples in new contexts, presentation order may matter less. In addition, the MRs in the chemistry triplet may be less like a continuum of concrete to abstract examples of a given concept and more like three very different aspects of the concept. For example, a realistic video of ice melting and a cartoon depiction of ice melting can represent more and less concrete examples of melting, respectively. In contrast, a realistic video of melting, a cartoon depiction of molecular movement during melting, and the chemical symbols for melting are less like different examples of melting, but instead, are more like three different dimensions or perspectives on the same phenomena that highlight very different information.

Second, the experiments reveal unbalanced or asymmetric student understanding of chemistry. Students were better at translating from concrete to abstract representations vs. abstract to concrete representations, regardless of instructional condition for both experiments. In other words, students apparently possessed an asymmetric understanding of phase changes because they exhibited a greater ability to translate from representation A to representation B (i.e. concrete-to-abstract) as compared to translating from representation B to representation A (i.e. abstract-to-concrete).

Little published work has examined the idea of symmetric and asymmetric understanding of and translation between MR. In mathematics, symmetric understanding has been suggested as a necessary requirement for a complete understanding (Rider, 2007), and one study found asymmetric understanding in math students who were more proficient at translating from equations to graphs versus translating from graphs to equations (Yerushalmy, 1991). The same study found that students were instructed to generate graphs from equations more often than the reverse (Yerushalmy, 1991), so asymmetric understanding may be a result of asymmetric instruction and/or assessment.

Depending on the specific concept and even the scientific domain, different translations may be more or less challenging for students. The nature of the subject itself could foster asymmetric understanding, which may be further compounded by or result in asymmetric instruction. For example, in chemistry, the macroscale representation is usually more familiar and more concrete to students (e.g. melting of an ice cube), but in astronomy, the macroscale may be so expansive (e.g. stars light years away and appearing as points of light) as to be unfamiliar and less concrete to students. Students who exhibit stronger ability to translate from concrete-to-abstract vs. abstract-to-concrete in chemistry may exhibit the opposite asymmetry in astronomy. Even within one domain, such as chemistry, different asymmetries may exist when translating between MRs for different concepts.

Conclusions

This study shows that the order of MR chemistry instruction by levels of concreteness does not impact student understanding and that comprehensive MR assessments reveal asymmetric understanding of chemistry. First, the order of presenting macroscale, nanoscale, and symbolic representations of chemistry in very brief instructional periods may not matter as much as providing instruction on all three corners of the chemistry triplet in any order to develop more expert understanding. Alternatively, the pedagogical approach may be related to the ideal order of presentation. For more passive pedagogy, such as the viewing of video lectures in this study, the order may not have an effect, but for more active learning methods, such as problem-based and inquiry-based learning, the presentation order may have a greater role (e.g. the problem or question being investigated may benefit from initially being presented at the concrete macroscale). For any approach, MR instruction should explicitly teach translation between representations in multiple directions to develop more symmetric understanding and translation ability. Such an approach may help students move beyond one mode of thinking to develop stronger conceptual understanding of a subject.

Second, we find asymmetric understanding even after MR instruction on all three corners of the chemistry triplet. Typical chemistry instruction does not cover all three corners to the same extent but rather focuses on symbolic representations, and our ongoing research confirms that additional asymmetries can exist when instruction is limited to fewer corners. Further research may also ascertain whether asymmetries occur across scientific domains as well as elucidate the role of asymmetries in pedagogy.

Importantly, the use of MR assessments may play a critical role in framing MR instruction and research on MR instruction. Assessments not only reveal the limits of student understanding, but they also circumscribe the range of understanding that students can demonstrate. Because the types of assessments signal to students what concepts and skills they should learn, asymmetric assessments focus students on developing asymmetric understanding and translation skills. Designing and implementing comprehensive MR assessments that translate in multiple directions would be more likely to promote student ability to translate in all directions. In other words, a greater focus on MR assessment (i.e. MR testing as part of teaching) would enhance MR instruction for all students (primary, secondary, tertiary). Such assessments would also be useful for informing the instructional design cycle by indicating the types of translations that are most challenging for students.

Similarly, the design of symmetric assessments is an area where further research is needed for all levels (primary, secondary, and tertiary) of MR instruction. As found in this study, assessment design revealed more about student performance than pedagogy design. There is a tendency in the research to compare different types of instruction more than different types of assessments, but for investigations of MR instruction, an increased focus on the assessment design may yield useful insights about highly effective MR instructional approaches. It is likely that different pedagogies bias student learning toward asymmetries in MR translation but need symmetric assessments to identify the asymmetric performance.

Finally, MR and concreteness fading are broad concepts encompassing multiple modes of thinking. Although the approach in this study may not apply to all types of MR, it may

Table 3. Multiple levels of concreteness in representations from different disciplines.

Math	Physics	Chemistry	Biology
Concrete example	Macroscale	Macroscale	Macroscale
Faded example	Invisible (forces)	Nanoscale	Microscale
Symbolic notation	Symbolic	Symbolic	Biochemical

Source: Adapted from Johnstone (2000a) and McNeil and Fyfe (2012).

be relevant to disciplines that utilize models potentially analogous to the chemistry triplet (Table 3).

The ability to translate between MR goes beyond understanding and learning science and math in academic contexts. Phenomena such as traffic jams, global trade, poverty, and the preservation of ecosystems all function at multiple levels, with different information and concepts relevant at each level (Holland, 2006). Information about these real-world problems are presented using MRs, and being able to translate effectively between these representations is critical for decision-makers and stakeholders. Developing effective MR pedagogy and assessments is a modest but crucial contribution that educators and educational researcher can make.

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No potential conflict of interest was reported by the authors.

Notes on contributors

Yulan Lin graduated with honors with the Bachelor of Science degree in chemistry from California State University, Los Angeles in 2014.

Ji Son is an assistant professor of psychology at California State University, Los Angeles.

James A. Rudd II is a professor of chemistry and biochemistry at California State University, Los Angeles.

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