Instructional Framing for Nanoscale Self-Assembly Design in Middle School: A Pilot Study

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Abstract

The effects of the sequencing of the introduction of domain-specific terminology on students' ability to perform nanoscale self-assembly design tasks were examined with middle school students. An instructional sequence where the design tasks were introduced using morphological descriptors and was subsequently bridged to the domain terminology only after the design experience allowed students to "practice" (practice-framed group), was compared to traditional instruction where domain terminology was used from the outset (domain-framed group). Performance on generative and predictive design tasks was assessed. The practice-framed group performed significantly better than the activity-framed group on the generative task, but no effect of treatment group was found on the predictive task. Overall, students demonstrated the ability to perform nanoscale design tasks.

Problem statement

Advances in the fields of nanoscale science and engineering are proceeding at such a rapid pace that it is estimated that a workforce of 2 million will be needed by 2015 (Roco, 2003). Scientists in this area have made several calls for nano-science education as they foresee need both to build that workforce pipeline (Chang, 2006; Foley & Hersam, 2006) and to broaden the general public understandings of the technical, social, and ethical implications of nanoscale research and development (Baird & Vogt, 2004). Thus, it is important for education researchers to study how students learn about nanoscale concepts and when and how these concepts should be incorporated into the curriculum in grades middle school, high school, and post-secondary education.

This line of research is a challenging endeavor since nanoscience is rarely included in science curriculum due to its lack of direct inclusion in the current U.S. educational standards (AAAS, 2001; NRC, 1996). Teachers already struggle to adequately cover the ever-expanding list of concepts they must teach for state local assessments, and rarely have the flexibility to include nanoscience in their science classrooms. In addition, few professional development opportunities are available to allow teachers gain understanding of this budding area of science. Education researchers must impart on practitioners and policy makers the need and means for nanoscience to be integrated into science standards and curricula.

One of the "big ideas" of nanoscale science and engineering is the concept of *self-assembly* (Stevens, et al., 2007). With nanoscale components, it is difficult and inefficient to assemble larger structures by the traditional means of "picking and placing" pieces into desired configurations. An alternative approach to the assembly problem is to design the components and the fluid environment in which they are contained so that the disordered components autonomously organize themselves, without explicit manipulation, into the desired formation through the use of attractive and repulsive forces such as van der Waals interactions (Whitesides & Grzybowski, 2002). Example of molecular self-assembly include the folding of proteins to form quaternary structures and construction of nanoscale filters. Students will need to understand the properties of and the principles involved in self-assembly in order to understand the creation of nanoscale objects.

Since self-assembly is a design process, design-based learning strategies are an attractive vehicle for supporting student understandings of the phenomenon and developing design skill. Design-based learning is a popular type of inquiry-based pedagogy since it allows students to grapple with more real world-type problems than are typically introduced in the classroom while also developing advanced problem-solving skills (Kolodner, 1993; Fortus, et al., 2004). Research has demonstrated that this type of learning can also lead to substantial increases in science content knowledge and knowledge of scientific practices (Kolodner, et al., 2003; Mamlok, et al., 2001). Interestingly, students who frequently show the most gain from design-based learning experiences are those that are socio-economically disadvantaged and/or under-achieving students (Kolodner, et al., 2003).

This study examined whether middle school students are able to learn about nanoscale phenomena and perform self-assembly design tasks related to the domain. Additionally, it investigated the effects of the sequencing of the introduction of domain-specific terminology on students' ability to perform design tasks. In traditional science instruction, students are presented with a new topic and related terminology through a lecture by the teacher, which is often followed by some hands-on activity to further foster conceptual understanding and interest. However, research suggests that this framing of instruction in the domain may hinder student learning by evoking misconceptions and prior negative experiences with scientific language (Barnes, 1990; Dykstra, Boyle & Monarch, 1992), or by cognitively interfering with conceptual understandings (Schwartz & Martin, 2004). A sequence of instruction in which the design task is introduced using morphological descriptors and is subsequently bridged to the domain terminology only after the design experience allows students to "practice" in the domain and may mitigate those issues. In addition, by providing appropriate prior knowledge and a frame of reference to learn new information via direct instruction, students may acquire an overall deeper understanding of domain concepts (Schwartz and Bransford, 1998).

Method

The study was conducted at an middle school in May, 2007. Two sixth-grade classes with a combined total of 41 students served as subjects. Researchers spent four one-hour sessions with each class over five days. Each class received a session of traditional instruction on nanoscale self-assembly and three sessions of performing practice design tasks adapted from the Concord Consortium's Molecular Workbench Self-Assembly unit (Concord). To introduce the use of the simulation to accomplish design tasks, a progression of practice exercises were completed prior to attempting the post-unit assessment. Students progressed from an exercise on random motion of molecules to adding fixed-strength dipole charges and modifying the energy in the environment. Practice tasks entailed choosing the type and placemen of charges on differently shaped molecules in order to yield self-assembled aggregates in a desired arrangement. In these sessions, the basic concepts of molecular self-assembly were introduced, including dipole attraction and repulsion, dipole bonding, charge position, movement, system energy, molecular shape, and reversibility. However, the sequencing of the introduction of domain-specific nanoscale concepts and vocabulary varied between the two classes.

In the "domain-framed" treatment group, the phenomena were described in domain terms from the outset and followed the typical order of science instruction: formal instruction followed by more hands-on activities. In the "practice-framed" treatment group, the phenomena were described using morphological nouns (e.g., "blobs" instead of "molecules") and verbs common to younger learners (e.g., "sticking" rather than "bonding"); the design sessions were then followed by a "bridging lesson" that related the objects and verbs of the design activity to their domain-specific vocabulary and concepts.

Paper-and-pencil assessments of self-assembly design proficiency, in addition to other assessments, were administered to each group between the two instructional phases and again at the study's completion. In the first of two design tasks, students were given a target final aggregate shape to produce given a selection of possible molecules to use (Figure 1). Students were asked to *generate* a solution by selecting the components needed for the tasks and to place positive and negative charges on the molecules in order for self-assembly to produce the target shape. The second task required students to *predict* how a collection of molecules with given positive and negative charges might self-assemble (Figure 2).

The solutions of students who completed both the intermediate and posttests (18 in the domain-framed group; 14 in the practice-framed group) were coded according to their correctness and the efficiency of charge placement. Students received full credit for correct solutions, although those that were not efficient were coded accordingly. Partial credit was given for incomplete answers (the solution would lead to an incorrectly assembled aggregate or not all of the molecules were included in the answer). Solutions coded as incorrect received no credit.

Results

Across both treatment groups on the two design questions, students averaged 61% on the intermediate test and 77% on the posttest.

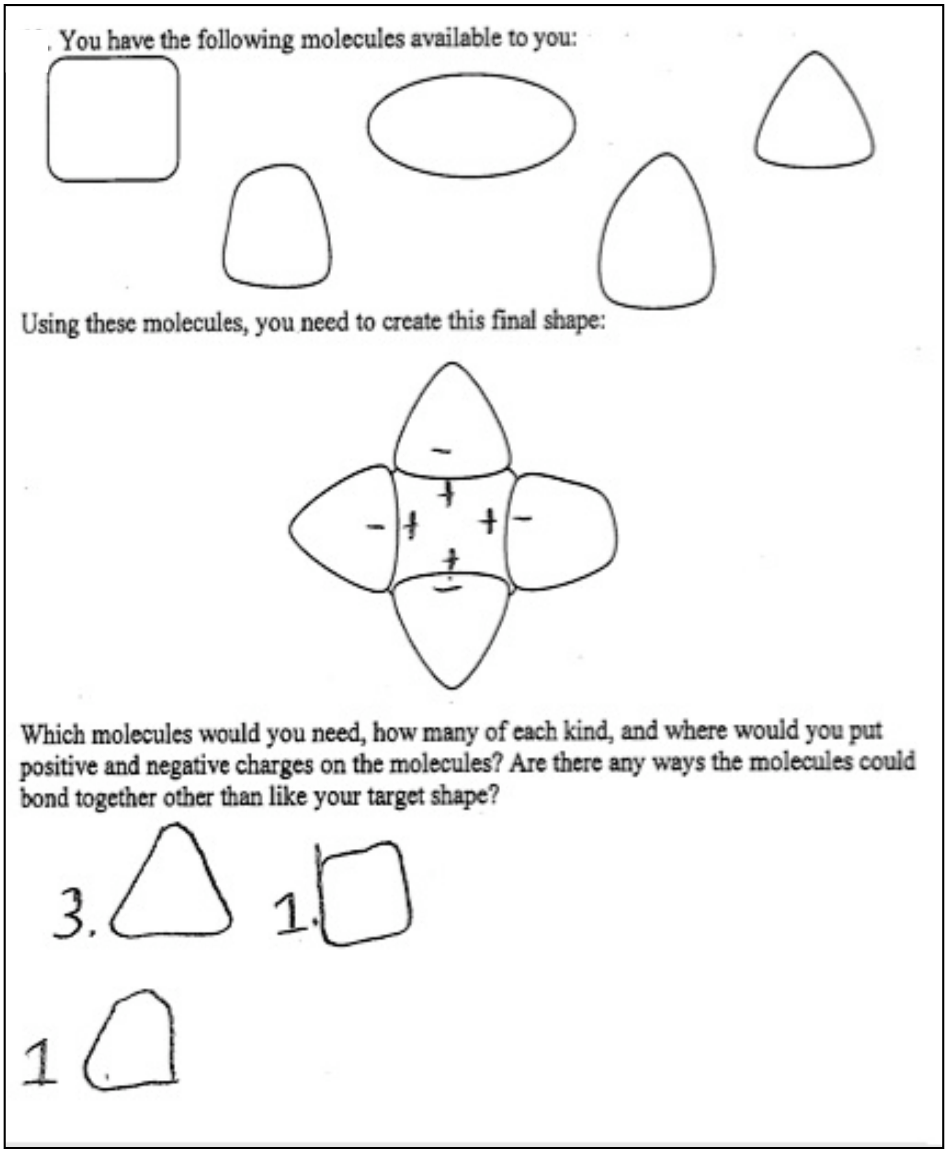

Figure 1. Generative design task. In this example, the student indicated the charge locations on the target configuration, and indicated how many of each component would be required to realize the (geometric) design.

Within the domain-framed group, the opportunity to use the computer simulation for design activities after didactic instruction had a strong effect on design outcomes. On the generative task, students improved from 28% to 67%, $t(17) = 3.76$, $p < .001$. An increase in performance from 47% to 78% also occurred on the predictive design question, $t(17) = 2.26$, $p < .05$.

In contrast, the addition of a bridging lecture following design practice did not lead to significant improvements in the practice-framed treatment group on the generative task (86% intermediate vs. 93% posttest), $t(13) = 1.47$, $p = .16$. There was a non-significant reduction in performance on the predictive task (82% intermediate vs. 71% posttest), $t(13) = 1.14$, $p = .27$.

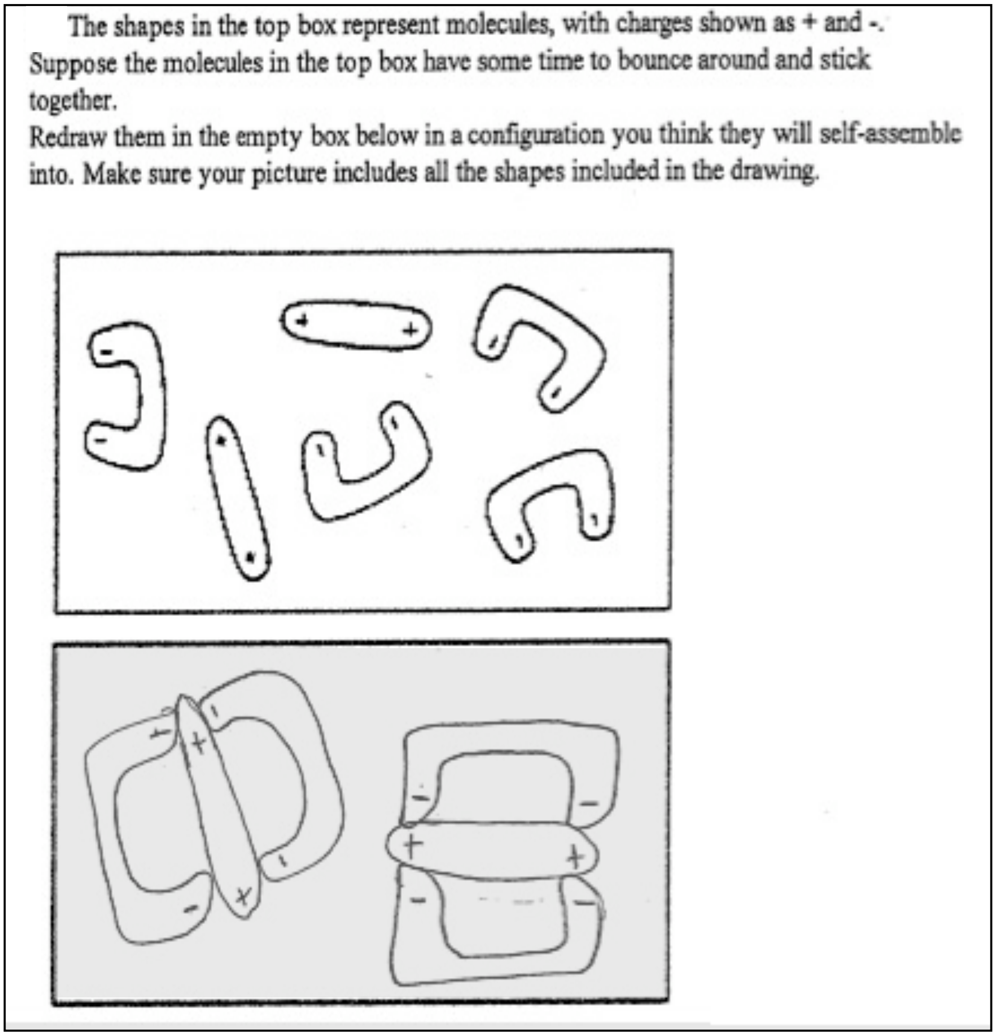

Figure 2. Predictive design task. In this example, the student produced normative (optimal) self-assembled aggregate (shaded area) from component moledules. Item based on Molecular Workbench Self-Assembly assessment (Concord).

On the posttest, there was a significant difference between the domain-framed (67%) and practice-framed (93%) groups on the generative task, $t(30) = 2.90$, $p < .01$. However, an effect of treatment group on performance on the predictive task was not found (72% domain-framed vs. 78% practice-framed), $t(30) = -0.40$, $p = .69$.

Characteristic errors on the prediction task involved the failure to account for all the component molecules in the final configuration, as well as the representation of binding loci involving more then two dipole charges (incorrect since at least two would be of the same polarity). On the generative task, 65% of the all students provided an optimal solution involving the application of eight dipole charges (as in Figure 1). With one exception, sub-optimal solutions tended to over-assign dipole charges, typically doubling or tripling the required number (though in one extreme case, suggesting the use of 37 charges).

Conclusions & Implications

On average, 77% of the sixth-grade students were able to provide correct answers between two molecular self-assembly design tasks by the end of the intervention. The use of an educational intervention that pairs instruction and practice seems to prepare students well for these tasks, despite their being young learners and new to nanoscience and design. To our knowledge, this is the first reported attempt to engage students at this age group in nanoscale self-assembly design; these results demonstrate that elements of these concepts and tasks are within the capabilities of early middle school students and may generate interest and open a window to the "big idea" of self-assembly prior to gaining a deep understanding of molecular structure and forces.

Design practice through the computer simulation had a strong impact on design performance in both treatment groups. Conversely, however, design capabilities did not change for the practice-framed group after adding a lecture. Not surprisingly, to learn to design well, students must practice in a dynamic environment that allows them to test their design ideas.

While treatment differences did not impact performance on a predictive task, they did have a significant effect on generative design performance. This gives rise to the possibility that the response to the ordering of treatments might be asymmetric with respect to type of task. One possible explanation is that the generative tasks provide more freedom in the types of answers students can provide. The cognitive load may be less for those not previously introduced to the domain (practice-framed group) and thus may provide greater liberty to explore design variants. Further research is necessary to determine an explanation for this asymmetry.

This study has several implications for design-based learning, nanoscience education, and curricula design in this domain. As one of the fundamental concepts of nanoscience, teachers will need to find an effective means to introduce their students to self-assembly. This study demonstrates that design-based learning opportunities show considerable promise as an instructional method for teaching self-assembly. It also suggests that by providing appropriate prior knowledge or experience before traditional instruction, the number of students showing mastery may be improved.

Further research on the effect of instructional framing is necessary to attain a complete understanding of its effect on students' learning. One possible area of investigation is the use of an alternative framing condition, in which domain-specific and neutral terminology are replaced by intentional mapping to an alternative content domain. Further distancing new concepts from the content domain and reframing the phenomena may have motivational and learning effects (Moher, et al., 1999).

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