RESPONSE CHARACTERISTICS OF MIDDLE SCHOOL LEARNERS' CRITIQUES OF NANOSCALE PHENOMENA REPRESENTATIONS

In this study, middle school students were presented with multiple representations of the same phenomenon (nano-scale DNA coupling) and asked to describe their advantages and disadvantages. Student responses favored response framings focusing on the visual and interactive affordances of representations in preference to "higher level" learning goals. Response distributions were largely independent of representation. The analysis suggested research questions concerning the effectiveness of introducing scaffolds to promote critique responses framed by issues of fidelity and the self-monitoring of learning and led to the re-design of materials for the next revision of the unit. Use of multiple representations was seen as important contributor to framings based on the fidelity of representations relative to the underlying (and, in the case of nano-scale phenomena, inaccessible) phenomenon.

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Introduction

Representations of phenomena play a central role in science education (Grosslight, Unger & Jay, 1991). Especially for younger learners, representational choice in instruction is often driven by the goal of abstracting the "big idea," with representations serving as received artifacts for learners. As learners mature, however, the representations themselves become productive grist for discourse. Coll, France & Taylor (2003), for example, emphasize the importance of providing opportunities for students to critique models in reference to the scientific phenomenon they represent, as this practice can support students in their understanding of both the phenomena and the nature of science. Gobert showed how a model-based unit that included critique of peer models could lead to content learning and epistemological gains (Gobert, 2003).

In this paper, we describe an instructional intervention in which urban 7th grade students were asked to critique (and implicitly compare) three representations of the same nano-scale phenomenon: DNA strand coupling. The learning objectives of the unit involved understandings of nano-scale structural units and behavior. DNA coupling is an example of nanoscale self-assembly; coupling occurs because nucleotide base pairs attract and bind when individual DNA strands come into proximity with one another. In the laboratory, scientists can design tethered nucleotide chains ("helper strands") that are capable of selectively capturing target partner strands, such as those associated with malevolent viruses (Cao, Jin & Mirkin, 2002).

This intervention was part of a design research project involving the introduction of nano-scale phenomena in a middle school biology unit on DNA. As part of the design iteration described here, we were interested in exploring representational critique as an instructional strategy, specifically using multiple representations of the same phenomenon. The provision of multiple representations may compensate for inadequacies of, or further refine, single representations of phenomena (Ainsworth, Wood & O'Malley, 1998; Cox & Brna, 1995; diSessa, 2005). While there is also evidence that the additional cognitive load associated with coordinating multiple representations can interfere with learning (Tabachneck, Leonardo & Simon, 1994), we believed that the students would be more likely to identify and recall representational features if offered contrastive versions.

Our hope was that asking students to engage in critiques would create demand for the underlying domain understandings. However, we didn't know what sense students would make of the task. The relative novelty of representational critique as an instructional practice led to an expectation that students' task perception would be strong mediated by their personal experiences and perspectives (Winne & Marx, 1983; Luyten, Lowyck & Tuerlinckx, 2001). If they interpreted the task in light of its entertainment or artistic value, for example, the critique would not provide much evidence of understanding. Consequently, rather than pursuing an instructional strategy, we decided to take the opportunity to obtain a baseline snapshot of how our young learners would respond to the multi-representation critique task at all. During the intervention, students were oriented toward critique through an activity in a distinct domain, but received no instruction in the performance of the task. We expected that the responses to the critique task could provide feedback for design revisions. We also hoped to find patterns of responses that might shed light on the kinds of "framings," or approaches to the task demands, that the learners adopted.

The use of a nano-scale DNA structure and behavior as the subject matter effectively "factored out" the influence of any prior experience with the phenomenon. However, we were interested also to see how the choice of nano-scale phenomena might be reflected in students' responses to the critique task.

Participants

The site of the intervention was a heterogeneously grouped 7th grade classroom of 31 students in a working class urban neighborhood school, of whom 28 completed the critique task. The school population is about two-thirds Hispanic/Latino and about one-fourth African-American/Black, with 95% of the students coming from homes designated as low-income. As a whole, the school is performing at the state (rather than the lower city) average, with approximately 80% of eighth graders meeting or exceeding state learning goals in mathematics, reading, and writing in 2008. The classroom teacher for the instructional intervention has nine years of teaching experience and a M.Ed., and was recently named science coordinator at the school.

Representations

Three representations of DNA were constructed (Figure 1), all based on a "string-of-pearls" framework that hides DNA backbone structure. The *drawing* representation depicted DNA as a linear chain of connected circles, each color-coded and labeled with one of the four letters T, G, C, and A (corresponding to the bases thymine, guanine, cytosine, and adenine, respectively). A legend reminded students that adenine forms a base pair with thymine (A-T), and that cytosine forms a base pair with guanine (C-G). This representation was designed to emphasize the overall architecture (ordered structure) and component elements (nucleotides) of DNA, and the linear representation facilitated comparison of nucleotide strand pairs.

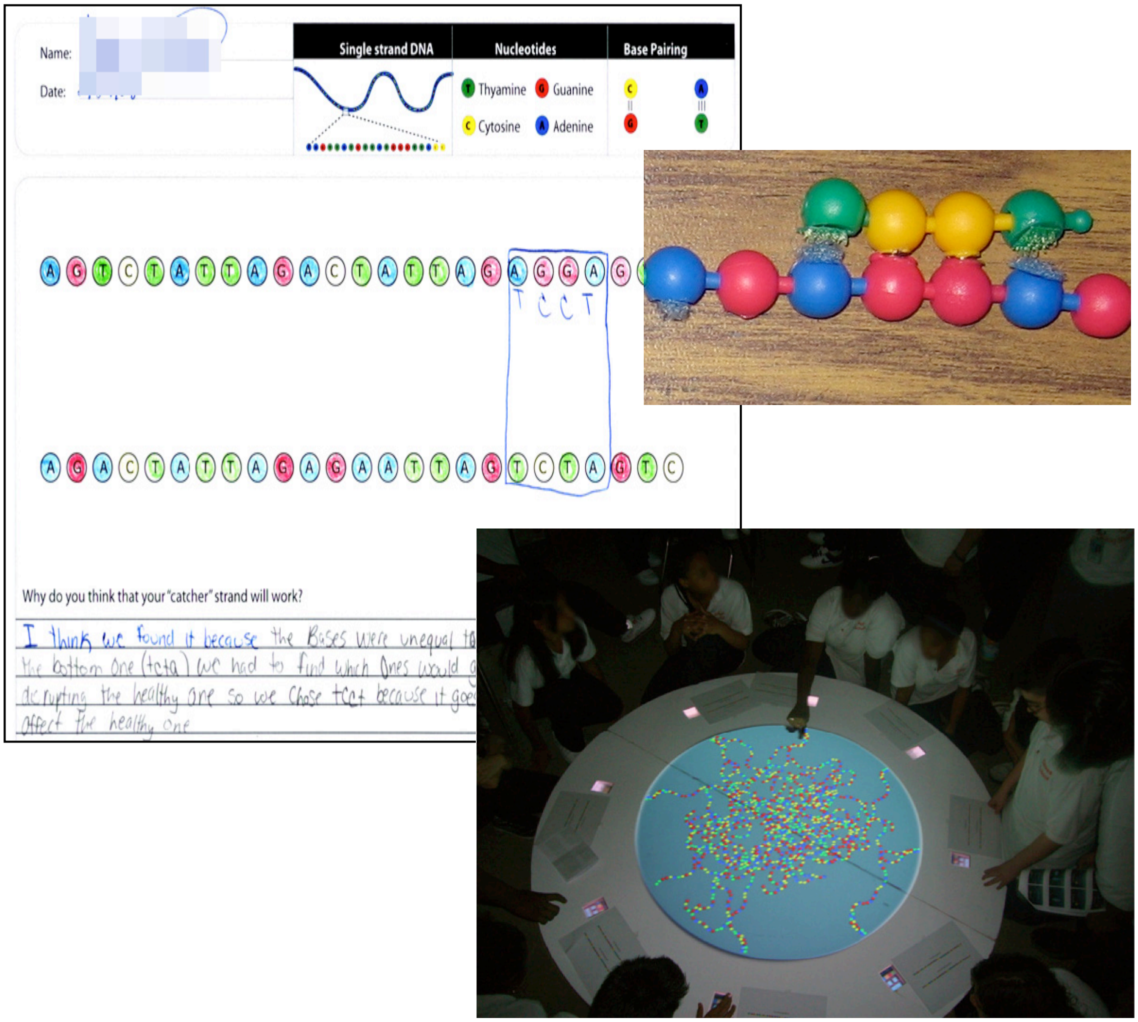
The *beads* representation used small, colored toy "pop-beads." Using the same color-coding as in the drawing representation, each bead was modified by the addition of a small piece of Velcro or by embedding a small, polarized magnet in the bead. This allowed us two model the two base pairings, assigning the magnets (both polarities) to one pair and the Velcro (both sides) to the other, so that beads would only "stick" to another bead if it formed a base pair. This representation reflected the flexibility and multi-dimensionality of DNA, and the magnets and Velcro afforded embodied experience with adhesion, attraction, and repulsion.

The *simulation* depicts a collection of moving, coherent chains of small colored circles "floating" on a large, horizontally projected circular display: a "cauldron" of different types of DNA strands. Along the periphery of the display are located other DNA "helper" strands, "anchored" to the cauldron wall. If nucleotide bases of sufficient length "match up" and it gets close enough, a floating strand will adhere to a helper strand. Here the goals were to highlight the dynamism of DNA and the cardinality of nano-scale phenomena.

Procedure

The representation critique task was introduced in the context of a one-week unit on the structure and behavior of DNA. The instructional design was developed in collaboration with the classroom teacher. The unit learning goals focused on DNA composition and structure (complex chains of molecules of one of four base types), base pairing, attractive forces, bond strength, and the design of complementary chains. The students in the class had previously been introduced to DNA within the context of genetics, but their textbook contained no discussion of the structure of DNA apart from an illustration of the double helix. Low scores on a unit pre-test indicated that the students brought very little knowledge about the subject to the unit (Lopez Silva, et *al.* 2009).

The unit began with a classroom activity in which the students constructed a blackboard table on which they listed advantages and disadvantages of two contrasting models of the Solar system. This activity was designed to orient students' attention toward issues of representation, and to provide them with experience in filling out a table very similar to that used in the DNA representation critique task. The teacher served as recorder, intentionally avoiding comments other those inviting more suggestions. Following a brief introductory presentation on the basic structure of DNA (nucleotides and base pairs), discussion turned to virus detection as an application of the underlying science.



Name: [redacted]

Date: [redacted]

Why do you think that your "catcher" strand will work?

I think we found it because the Bases were unequal t
the bottom One (tcta) we had to find which Ones would
derupting the healthy one so we Chose tcct because it goe
affect the healthy one

Figure 1. Three representations of DNA. Top left: Drawings of nucleotide chains. Top right: Pop-beads with magnets and Velcro. Bottom right: Projected video simulation of nucleotide chain movement and pairing.

Subsequent activity during the intervention centered around the use of the three representation, which were introduced on the first (drawing), third (beads), and fourth (simulation) days of the unit, in which students were asked to design "helper strands," which would 'capture' target viral DNA through nucleotide base pairings. Students were required to find solutions that addressed two criteria: (a) the catcher virus must be designed in such a way that it uniquely catches only the "bad" (target) virus among a set of multiple DNA single strands in the environment, and (b) the number of base pairs must be sufficient to ensure that there is adequate strength in the connection between the target virus and the catcher to overcome the turbulence in the environment.

Each representational form afforded a different technique for constructing and testing candidate catcher strands. In the drawing version, students specify catcher strand components by inscribing them adjacent to the target strand and comparing them with corresponding elements of non-target strands to ensure their selectivity. In the case of the beads, students assembled catcher strands by physically connecting the beads, then holding them up against the target to see if the magnetic poles and Velcro strips permitted adhesion. In the simulation, students designed their catcher strands one nucleotide at a time on a handheld PDA, then "attached" their candidate to the perimeter of a large "cauldron" full of target (and non-target) strands, observing whether their design was successful by seeing if it captured a target strand of the right type.

Students first developed solutions to this task using drawing and beads representations (in these activities, the minimum number of base pairs to ensure bonding was stipulated), then worked in small groups with the computer simulation, designing anchored nucleotide sequences that were attached to the rim of the simulated fluid container. In this activity, the minimum number of base pairings to ensure bonding was left as an empirical issue for students to resolve through experimentation with the system. The DNA critique task was given following the work with all three representations, and consisted of a 3x2 table with rows corresponding to the three representations and columns headed "advantages" and "disadvantages."

Results

Coding Learner Responses

Collectively, students provided 160 written responses to the task prompt (8 response fields were left blank). The responses were transcribed and shared among the authors, and who reviewed them with the goal of identifying distinctive clusters of statements that reflected possible response framings. From that process emerged a consensus on six categories, including framings related to enjoyment, the (visual and interactive) affordances of the representations themselves, task difficulty, representational fidelity, and domain understandings (Table 1). The responses were then coded independently by two of the authors. For each written response, raters identified one or more (in the case of compound responses) *assertions* contained within the response and then performed two codings: (a) assigning assertions to response categories, and (b) determining the "polarity" of the response, that is, whether the observation was a positive or negative response to the representation. The units of analysis are the 213 coded assertions that rose from this process (and not the students or their raw responses). A test of inter-rater reliability ($\kappa = 0.86$) showed strong agreement, and discrepancies were negotiated and resolved for all except two responses, which were not coded.

Learner Response Categories

Figure 2 shows the distribution of learner assertions by framing, including all assertions, positive or negative. The visual and interaction affordances of the representations were clearly the dominant framings for the students, accounting for almost 60% of student assertions. Responses were evenly distributed among the remaining framing categories, with the exception of explicit assertions of learning, which accounted for only about 5% of the assertions.

Table 1
Response framings and examples from data corpus

Response framing	Examples (positive, negative)
Enjoyment in using the representation (what was fun)	"The simulation was the funnest of them all", "The disadvantage was that it was kind of boring to me"
Visual affordances of the representation (what you can see)	"It was cool because we got to see the DNA moving around", "you can't see the name[s] of the different base[s]"
Interaction affordances of the representation (what you can do)	"I could make my own virus and remove bases whenever I want", "can't feel or touch DNA strands"
Difficulty of meeting the design task requirements (what was hard)	"Easy to work with", "It was much harder to check the sequence"
Fidelity of representation viz. underlying phenomenon (what was realistic)	"We got to work with the real thing", "Inaccurate size"
Value of representation in fostering domain *Understanding* (what helped you learn)	"We got to see the DNA up close and learn CTGA"[†], "I didn't like is it was difficult to understand"

[†] Response coded as positive for both the Visual and Understandings categories.

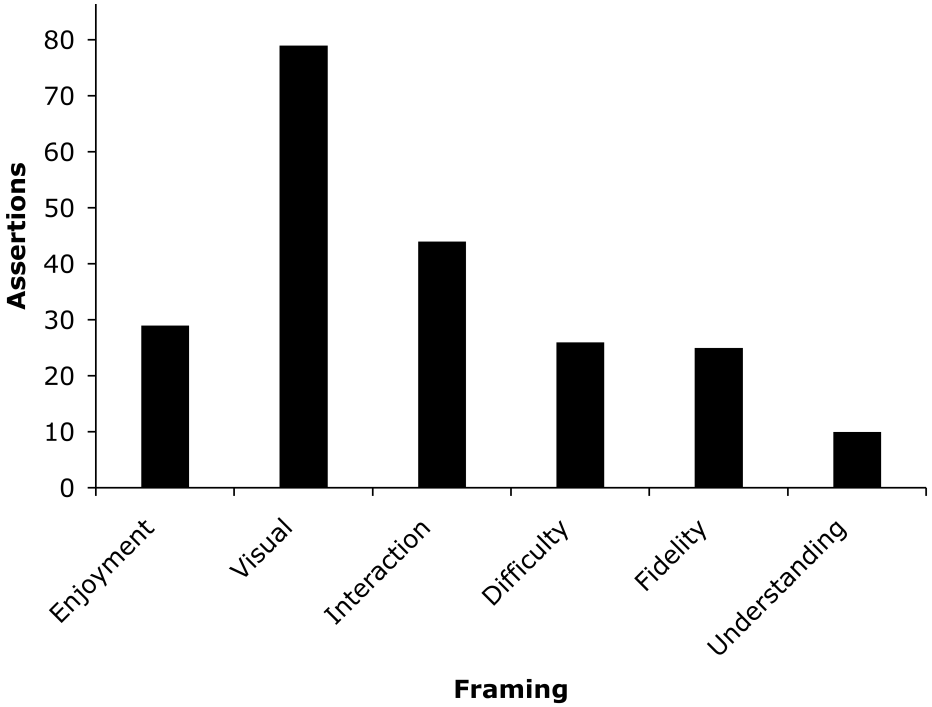


Figure 2. Frequency distribution of student assertions (N=213), by framing.

Response Polarity

Overall, there were about 20% more positive than negative assertions; students tended to be a bit more expansive in their positive responses, and most of the empty response fields were in the “disadvantages” column. (For the most part, though not always, students provided positive responses for “advantages” and negative responses for “disadvantages.”)

Figure 3 shows the relationship between response polarity and response framing. The distributions of positive and negative assertions across categories were distinctive ($\chi^2(5,N=213) = 17.8$, $p < .01$). The distribution of negative assertions was heavily skewed, with criticisms of visual features of the representations accounting for nearly half of all negative assertions. Positive assertions were spread more broadly among response framings.

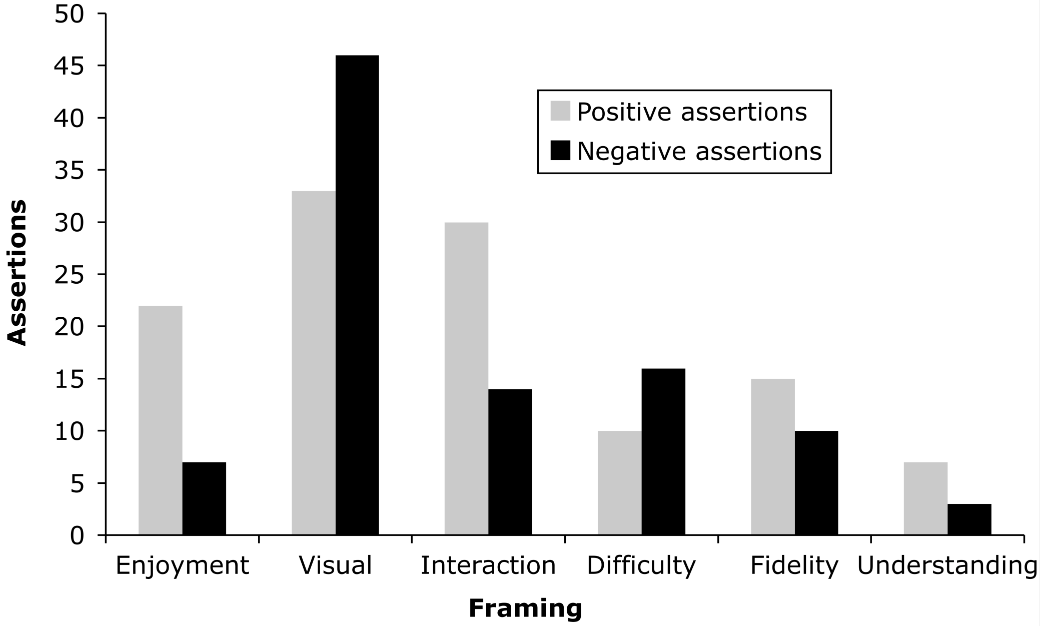


Figure 3. Frequency distribution of positive and negative student assertions (N=213), by framing.

Only two framing categories attracted more negative than positive assertions: visual affordances and task difficulty. Students were especially eager critics of limitations (limited acuity, absence of labels or color coding, etc.) in the visual features of the representations they utilized. Positive assertions were particularly dominant among learners adopting the enjoyment and interaction framings.

Representational Form

Up until this point, we have been characterizing the assertion corpus without respect to representational differences. The graph in Figure 4 shows how student assertions associated with specific representations were distributed among framing categories. While the distributions were distinctive ($\chi^2(10,N=213) = 27.1$, $p<.01$), the most notable differences owe to assertions of enjoyment in using the simulation and the lack of assertions regarding domain understanding when critiquing the beads or the simulation. Among other framing categories, the distributions are roughly congruent.

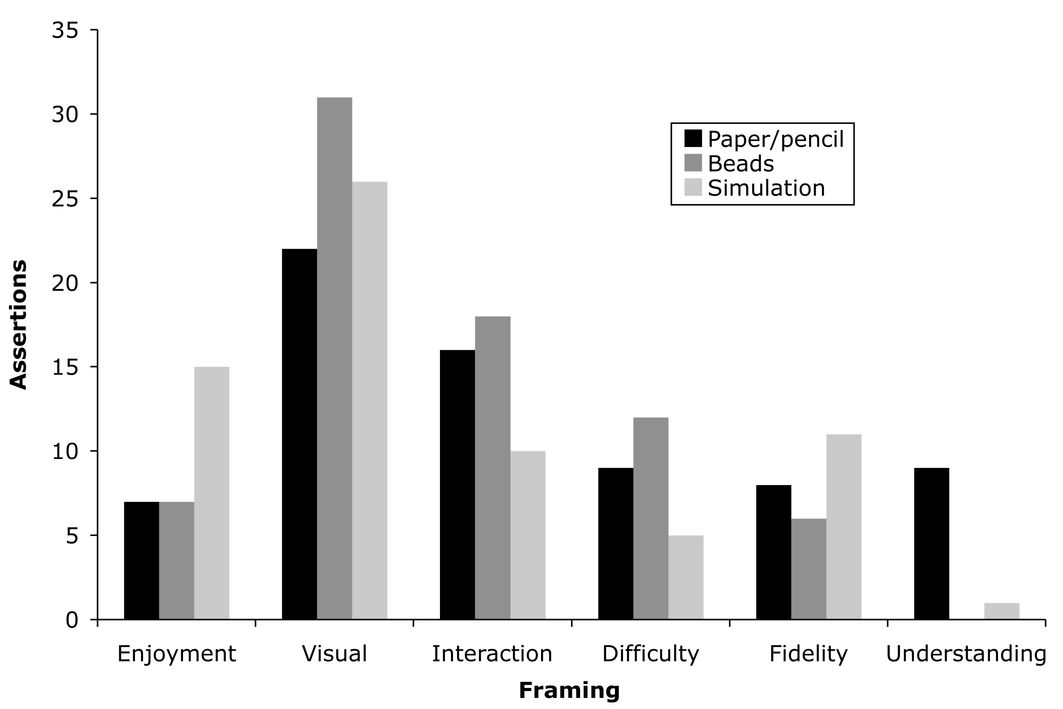


Figure 4. Frequency distribution of student assertions (N=213) per representation, by framing.

Form-Polarity Interaction

The distribution of response polarities by representational form (Figure 5) showed strong contrasts ($\chi^2(2,N=213)) = 20.4, p<.01$), with the simulation drawing relatively more positive assertions than either the drawing ($\chi^2(1,N=139) = 19.5, p<.01$) or beads ($\chi^2(1,N=142) = 10.6, p<.01$). The contrast between the drawing and beads was not significant ($\chi^2(1,N=145) = 1.6, p=.20$).

Table 2 provides the full distribution of assertions in the corpus by response framing, polarity, and representational form. As a general trend, distributions become more skewed as the representation moves from drawing to beads to simulation. In spite of learners' enthusiasm for the software, criticism of the simulation focused on detailed limitations of visual affordances. The beads and simulation elicited strong positive responses for their interactivity.

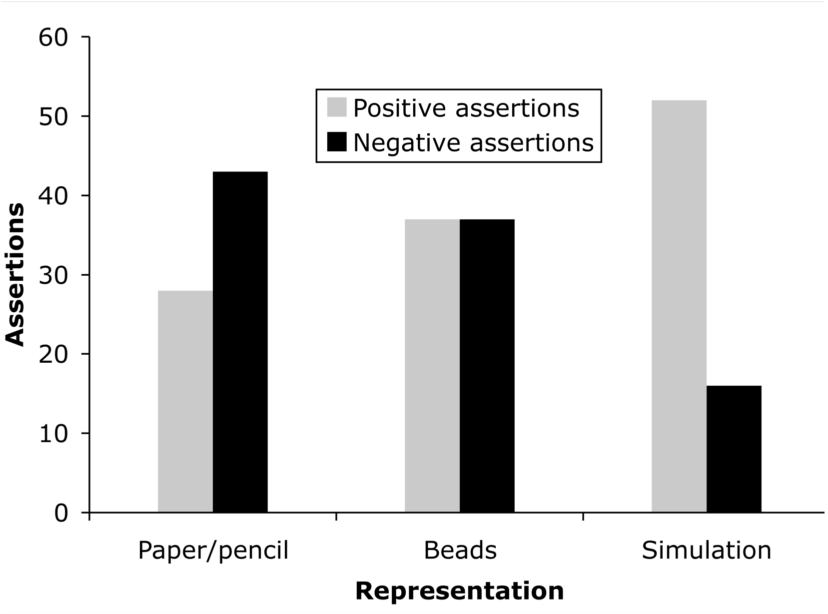


Figure 4. Frequency distribution of positive and negative student assertions (N=213), by representation.

Table 2
Interactions between representational form and response polarity

Response category	Drawing		Beads		Simulation	
	Positive	Negative	Positive	Negative	Positive	Negative
Enjoyment	2 (7%)	5 (12%)	5 (14%)	2 (5%)	15 (29%)	0 (0%)
Visual	9 (32%)	13 (30%)	10 (27%)	21 (57%)	14 (27%)	12 (75%)
Interaction	4 (14%)	12 (28%)	16 (43%)	2 (5%)	10 (19%)	0 (0%)
Difficulty	3 (11%)	6 (14%)	3 (8%)	9 (24%)	4 (8%)	1 (6%)
Fidelity	4 (14%)	4 (9%)	3 (8%)	3 (8%)	8 (15%)	3 (19%)
Understanding	6 (21%)	3 (7%)	0 (0%)	0 (0%)	1 (2%)	0 (0%)
Total	28 (39%)	43 (61%)	37 (50%)	37 (50%)	52 (76%)	16 (24%)

Columns sum to 100% except the last row, which reflects percentages within representations.

Discussion

The students in this class evidenced a surprisingly sophisticated response to a demand that was outside of their normal classroom practice. Tasked to critique multiple representations of the same phenomenon, they backgrounded issues of enjoyment, focusing instead on features of the representations that afforded interaction, information extraction and, albeit to a lesser extent, task satisfaction, representational fidelity, and understanding. They exhibited a willingness to be selectively laudatory and critical, and were specific about the representational features they found helpful or disadvantageous. Pre-post assessment showed significant gains in domain understanding (Lopez Silva, et *al*, 2009).

A clear outcome from the current analysis is the predominance of attention to the visual (2 of every 5 assertions) and interaction (1 of every 5 assertions) affordances of representations in student responses. For the most part, these students interpreted critique as a request for commentary on the quality of representations with respect to the information that they made accessible and the manipulations that they permitted. This is not an unreasonable response when confronted with novel materials; the students felt qualified to comment on affordances independent of the underlying science, and particularly empowered with respect to criticisms of the visual affordances of the representations.

However, attention to what might be considered the "surface features" of representations may come at the expense of broader instructional goals, including the evaluation of a representation as a working medium ("difficulty") within a goal-directed activity, the relationship between the representation and the phenomenon it is intended to illustrate ("fidelity"), and the self-monitoring of learning within the activity ("learning"). Taken together, assertions in these framing categories occurred only half as frequently as those concerning visual and manipulative affordances.

The arrangement of the framing categories in the figures and tables above is not arbitrary; the order is intended to suggest a roughly ordinal scale of sophistication in learners' interpretation of representations. At one extreme are learners who act as "members of an audience," evaluating the activity with reference to their personal enjoyment. "Observers" attend to the visual details of the representation, while "actors" explore the manipulation space. "Tool users" (those concerned with task difficulty) have moved beyond observing or interacting with the representation for its own sake, and focus on how those affordances impact task completion; these students are beginning to evaluate the representations within a specific context. "Science learners" (fidelity) focus directly on the link between representation and phenomenon; to adopt this framing requires that the student have developed a mental model of the phenomenon sufficiently distinct from the representation to be used as a basis for comparison. "Self-monitoring learners" attend to the ways in which representations impact (or fail to impact) their learning.

At the least, it is not unreasonable to conjecture that a distribution skewed more toward what could be considered the "higher level" framings might align with deeper domain and metacognitive understandings (making the distribution itself a rough diagnostic). If this were generally the case, then instructional scaffolding that focused on representational fidelity and the self-monitoring of understanding could potentially promote frame shifts associated with greater learning gains. In our current work, we are testing such scaffolds to see (a) whether we can actually induce the desired changes in the distribution of student responses to the representation critique task, and (b) how learner domain understandings are impacted through their introduction.

While the representation used, we would argue, did not have much impact on the distribution of assertions across framing categories, there were some notable exceptions.

Students clearly enjoyed interacting with the simulation and found the most positive things to say about it, but this due at least in part to its novelty. One intriguing outcome was the dominance of the paper-and-pencil drawing representation with respect to the elicitation of responses citing learning. A potential cause might be the association between paperwork as a medium for classroom learning; working with the beads and simulation may have shifted students away from an awareness of themselves as being within a learning situation. Alternatively, the visual affordances of the drawings (uniquely, continuous access to base labels) might make the representation more meaningful (and hence perceived as promoting learning) to learners, even if they like it the least and complain about it the most.

The critique data did lead to changes to our representations, and to the discourse surrounding their introduction and use. The "drawing" version now consists of two separate pieces of paper that can slide along one another, allowing for more facile comparison of nucleotide base pairing segments. The lack of base labels in the bead and simulation representations was addressed through explicit discussion of the lack of such labels on actual bases (incidentally reinforcing attention to fidelity) and by creating a large wall chart showing the color-to-label correspondence for easy reference.

It is interesting to speculate on how the nature of the phenomenon itself might have impacted response distribution. The predominance of the visual affordance framings might be explained, in part, by the lack of accessible phenomena; lacking experience, learners' sole source of information about the phenomena are the representations themselves, hence requiring close attention to the visual and manipulative features of the representations in order to construct learners' mental models. The lack of direct experience with nano-scale phenomena in general (and DNA in particular) would seem a significant roadblock to assertions regarding fidelity, which requires access to both the representation and a (alternative) mental model. (In retrospect, the fact that the responses appeared in the numbers that they did seems at least modest evidence that a segment of the class was developing those mental models.)

If representational fidelity is a desirable response framing, it would seem that multiple representations are a near necessity when working with nano-scale phenomena. By offering learners multiple representations of the same phenomenon, they can see how features of the phenomenon common among representations are depicted; this allows learners to better understand the invariants and the range of representational freedom relative to the phenomenon. The use of a single representation runs the risk of convolving the phenomenon and the representation, and depends solely on discourse as the basis for the development of a mental model sufficiently distinct to use for critique.

Conclusion

In this study, middle school students were presented with multiple representations of the same phenomenon (nano-scale DNA coupling) and asked to describe their advantages and disadvantages. Student responses favored response framings focusing on the visual and interactive affordances of representations in preference to "higher level" learning goals. Response distributions were largely independent of representation. The analysis suggested research questions concerning the effectiveness of introducing scaffolds to promote critique responses framed by issues of fidelity and the self-monitoring of learning and led to the re-design of materials for the next revision of the unit. Use of multiple representations was seen as important contributor to framings based on the fidelity of representations relative to the underlying (and, in the case of nano-scale phenomena, inaccessible) phenomenon.

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