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Probing Middle School Students' Knowledge of Thermal Expansion and Contraction through Content-Aligned Assessment

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Abstract

This paper describes how we use pilot testing to gain insight into middle school students' thinking about thermal expansion and contraction, and how we use that information to improve the test items we are developing. From the students' responses to pilot test items, we learned that students find it considerably more difficult to link the macroscopic and the molecular level phenomena related to thermal expansion than simply to describe what is happening at the molecular level. This led to revisions of both the test items and our expectations for students. This study is part of a larger project to develop an online collection of student assessment items in science that are precisely aligned with national standards. Each item is developed and analyzed using a procedure designed to evaluate an item's match to important science ideas and its overall effectiveness as an accurate measure of what students do and do not know about those ideas. During the item development procedure, student feedback is obtained through pilot testing and interviewing.

Introduction

As K-12 educators prepare for widespread testing in science mandated by federal *No Child Left Behind* legislation, concerns are growing about the quality of science assessments and their alignment to state and national content standards. In response to these concerns, we are developing an online collection of student assessment items in middle school science that are closely aligned to those standards. Each item is analyzed using a procedure designed to evaluate an item's match to important science ideas and the item's overall effectiveness as an accurate measure of what students do and do not know about those ideas. This paper describes how we use pilot testing to obtain input from students as part of our item development process. The results of pilot testing provide information about student thinking about the ideas being targeted and the items themselves, and this information is then used to revise the test items and, sometimes, the expectations we have for students.

In this paper, we focus on the targeted idea that thermal expansion and contraction can be explained by the behavior of atoms and molecules. This idea appears in *Benchmarks for Science Literacy* as the statement: "Increased temperature means greater average energy of motion, so most substances expand when heated" (AAAS, 1993, p. 78). It can also be found in the 2009 NAEP Framework as: "Properties of solids, liquids, and gases are explained by a model of matter that is composed of tiny particles in motion" (National Assessment Governing Board, n.d., p. 30). We were especially interested to know if students would make the link between the behavior of atoms and molecules and the macroscopic phenomena of thermal expansion and contraction. We also wanted to know if students would respond differently when asked a question just at the atomic/molecular level versus at the atomic/molecular level applied to macro level phenomena. We know from the literature that students can often describe what is happening at a molecular level without being able to apply this knowledge to the corresponding macroscopic phenomena (Lee et al., 1993; Gopal et al., 2004; Nakhleh et al., 2006). In a study of student understanding of the behavior of atoms and molecules as related to states of matter and changes of state, Nakhleh et al. speculated that "students may have simply memorized the scientific fact that 'all matter is made of atoms' without internalizing it. This would explain why they could not apply this knowledge in their explanations of the macroproperties of matter" (Nakhleh et al., 2006). In the present study, we explore whether this tendency on the part of students not to apply knowledge of the behavior of atoms and molecules to macro level phenomena is also true for thermal expansion and contraction. The findings could have important implications for the design of assessments on the topic of atoms and molecules as well as for classroom instruction.

Methodology

Item Development. The procedure we used to develop assessment items involves three stages: (1) clarifying the targeted learning goal, (2) designing assessment tasks that are closely aligned to the specific ideas in the targeted learning goal, and (3) revising items based on data obtained from interviewing and/or pilot-testing items with students. The process aims to achieve a precise link between a targeted idea and the test item itself.

Key ideas. Although state and national content standards provide important guidance to assessment developers regarding what students should know in science, these statements often are not enough by themselves to specify exactly what students should know. To increase the precision of the alignment between content and assessment, we further subdivide the content standards into finer-grained statements of knowledge, or *key ideas*, and then we clarify each key idea by indicating what it is that we expect students to know about that idea and what the boundaries of that knowledge are for purposes of assessment. In the case of thermal expansion and contraction, the key idea says:

> *For any single state of matter, changes in temperature typically change the average distance between atoms or molecules. Most substances or mixtures of substances expand when heated and contract when cooled (*based on benchmark *4D/M3b) (*AAAS, 1993, p. 78).

Clarification statements. Key ideas are then elaborated to specify exactly what we expect students to know about the key idea. The following is an excerpt from the clarification statement for thermal expansion and contraction:

> *Students should know that as the temperature of a substance increases, the average distance between the atoms/molecules of the substance typically increases, causing the substance to expand. Students should also know that as the temperature of a substance decreases the average distance between the atoms/molecules typically decreases, causing the substance to contract. Students are expected to know that this expansion or contraction can happen to solids, liquids, and gases. They are also expected to know that expansion or contraction due to changes in temperature can also happen to mixtures of substances. Students are expected to know that expansion or contraction due to changes in temperature is not permanent (e.g., objects that expand when heated then contract when cooled). They are expected to know that the number of atoms and the mass of the atoms do not change with changes in temperature.*

Pilot Testing. The pilot testing reported on here included students in grades 7 – 9 from two school districts in different parts of the country. The demographic characteristics for each district are as follows: (1) A middle school and a high school in a northeastern suburb having a student population that is 40% White, 48% African American, and 8% Hispanic, with 25% of the students eligible for free and reduced lunch; and (2) a middle school in a small southern town with a student body that is 70% White and 24% African American, where 33% of the students are identified as economically disadvantaged.

During pilot-testing, students responded in writing to the following questions about each item:

1. Is there anything about this test question that was confusing? Explain.
2. Circle any words on the test question you don't understand or aren't familiar with.
3. Is answer choice A correct? Explain why. Yes No Not Sure
4. Is answer choice B correct? Explain why. Yes No Not Sure
5. Is answer choice C correct? Explain why. Yes No Not Sure
6. Is answer choice D correct? Explain why. Yes No Not Sure
7. Did you guess when you answered the test question? Yes No
8. Please suggest additional answer choices that could be used.
9. Was the picture or graph helpful? If there was no picture or graph, would you like to see one?
10. Have you studied this topic in school? Yes No Not Sure
11. Have you learned about it somewhere else? Where? Yes No Not Sure

From their written responses, we are able to determine: (1) whether students used the targeted idea to answer the question or if they used other knowledge or test taking strategies instead, (2) whether the item was comprehensible to them, and (3) whether the answer choices were plausible to them. Mismatches between the answer choices that students select and the reasons they give provide us with information about whether the item is likely to yield false positive or false negative results. Student responses also provide information regarding student misconceptions.

The Test Items. We compared students on two versions of a test item designed to assess their understanding of thermal expansion and contraction. In the first version, students were asked to identify what happens at the atomic/molecular level when a solid substance (an iron frying pan) is cooled (i.e., that the distance between the atoms decreases). In the second version, the students are asked to predict what will happen macroscopically to a frying pan when it cools (i.e., that the pan gets a little smaller) and to provide a molecular explanation. The students also received three additional items aligned to the thermal expansion/contraction idea and four items aligned to the idea that all atoms are in constant motion. The contexts of these additional items are outlined in table 2. A randomly selected half of the students in each classroom (n=32) answered version 1 of the frying pan question and half (n=30) answered version 2. All students (n=62) received the other seven items about thermal expansion and the behavior of atoms and molecules.

Version 1:

After cooking breakfast, a cook places a hot iron frying pan on the counter to cool. What happens as the iron pan cools?

A. The iron atoms get heavier.
B. The iron atoms decrease in size.
C. The number of iron atoms increases.
D. The distance between iron atoms decreases.*

Version 2:

After cooking breakfast, a cook places a hot iron frying pan on the counter to cool. What happens as the iron pan cools?

A. Even though you cannot see it, the pan gets a tiny bit smaller because the iron atoms decrease in size.
B. Even though you cannot see it, the pan gets a tiny bit smaller because the distance between iron atoms decreases.*
C. Even though you cannot feel it, the pan gets a tiny bit heavier because the iron atoms increase in mass.
D. Even though you cannot feel it, the pan gets a tiny bit heavier because the number of iron atoms increases.

Determining the equivalence of the two comparison groups. The two comparison groups (students who received version 1 or version 2 of the frying pan item) were compared on how they performed on the other seven items that they took in common to see if the two groups that were randomly assigned to one of the two frying pan items were equivalent groups. If differences appeared on some items but not others, we also wanted to see if there was a pattern to those differences. We thought that perhaps answering version 1 versus version 2 of the frying pan item might have a differential effect on how students answered one or more of the other items.

Findings

Version 1: Identifying the atomic/molecular explanation

For version 1, 56% of the students correctly chose answer choice D, indicating that they knew that the distance between the atoms decreases as the temperature decreases (see table 1). About 25% of the students chose one of the three distractors, and 19% said they were "Not Sure" or did not choose any answer choice. In their written comments, four of the students (12.5%) indicated that they thought the *mass* of the atoms would change, four (12.5%) indicated that they thought the *size* of the atoms would change, and three (9%) thought that the *number* of atoms would change. Similar misconceptions have been previously documented in the research literature (Griffiths et al., 1992; Lee et al., 1993).

Version 2: Linking the atomic/molecular explanation to the macroscopic phenomenon

When students were asked to predict what would happen to the frying pan at the macroscopic level and link that prediction to the behavior of atoms/molecules, performance fell off considerably. Only 13% of the students accurately predicted that the frying pan would get smaller as the distance between atoms decreased, and 50% of the students said they were "Not Sure" what the correct answer was. The difference in student performance is significant at the 0.01 level of significance ($t=3.93$, $p<0.01$).

Table 1: Number and percentage of students who chose each answer choice.

Frying Pan Version 1: Atomic/Molecular only	B (size)	D* (distance)	A (mass)	C (number)	Not Sure	Total
n	5	18	2	1	6	32
%	16%	56%	6%	3%	19%	100%
Version 2: Macro + Molecular	A (size)	B* (distance)	C (mass)	D (number)	Not Sure	Total
n	2	4	6	3	15	30
%	7%	13%	20%	10%	50%	100%

After studying the students' written comments, it was clear that students had difficulty linking the macroscopic and the molecular level phenomena. In particular, many of them could not accept the idea that a frying pan actually changes size when it is cooled. In fact, 50% of the students said that neither answer choice A nor B, both of which included the statement that the frying pan would get smaller, could be correct. It is likely that the students resisted accepting the fact that the pan actually gets a little smaller because they have not directly observed it happening at the macroscopic level. About answer choices A and B, one student wrote: "A frying pan can't get any smaller than it already is." Another student thought that the pan getting smaller (answer choices A and B) was "unrealistic," and when choosing answer choice D, wrote: "it could be D because the others don't make any sense." Another student thought that if the pan got smaller each time it cooled, eventually there would be no pan left.

Results from other items. When comparing students who took version 1 versus version 2 of the frying pan item, no significant differences were found on any of the items that test student knowledge of the idea that atoms are in constant motion (see table 2). Based on student performance on those four test items, the two groups appear to be equivalent. Furthermore, the performance of the two groups did not differ significantly on two of the three thermal expansion/contraction items (the concrete sidewalk item and the bottle item) that we used for comparison purposes (see table 2). This again supports our assumption that the test packets were randomly distributed and that the two groups of students could be considered statistically equivalent. However, for one of the items (thermometer), students who received version 1 of the frying pan item performed significantly better than students who received version 2 ($t=2.53$, $p<0.02$). Although we recognize that it is possible that the version of the frying pan item that students received had some differential effect on how they answered the thermometer item, we do not know at this time what that influence may have been or how it might operate.

Table 2: Number and percent correct for all items by version of frying pan item taken.

Idea	Item Context	Students who took Version 1		Students who took Version 2		t	p
		%	n	%	n		
Thermal Expansion and Contraction	The spaces between sections of a concrete sidewalk get narrower in the summer because the concrete expands.	17%	30	22%	27	-0.523	0.603
	The distance between the atoms of a gas in a plastic bottle decreases as temperature decreases.	48%	31	35%	26	1.040	0.303
	The distance between the atoms of the liquid in a thermometer increases as temperature increases.	52%	27	21%	29	2.525	0.015
Motion of atoms	Water molecules will not stop moving.	40%	30	48%	25	-0.587	0.560
	Atoms of a solid piece of glass always move.	32%	31	46%	26	-1.065	0.291
	If the temperature of a liquid remains constant, the average speed of the molecules will remain the same.	48%	27	58%	26	-0.686	0.496
	If the temperature of a substance increases, the average speed of the molecules will increase.	72%	32	73%	26	-0.100	0.921

We then looked more closely at the responses of students to each of the thermal expansion items to see if those responses told a consistent story across the items.

Concrete sidewalk item. The concrete sidewalk item asked the students to *predict* what would happen macroscopically to the spaces between the concrete sections on a hot day (and by extension, what would happen to the concrete sections). Students did not have to link the macroscopic phenomenon to the behavior of atoms and molecules. The answer choices allowed students to select whether the spaces would get wider, get narrower, do neither, or do both. Both groups performed about the same on this item—17% correct for students who took version 1 of the frying pan item and 22% correct for students who took version 2 of the frying pan item (t= -0.523, p=0.603). For the two groups combined, approximately 19% (11 students) correctly answered that the spaces would get narrower on a hot day. Approximately 9% (5 students) thought the spaces would get wider and about 10% (6 students) thought the spaces would both get wider and narrower. The most popular answer choice was that the spaces would neither get wider nor narrower as the temperature increased. Twenty-three students (40%) selected this answer choice.

From their written responses, it is clear that many of the students did not know that solids can expand and contract. One student wrote "I don't think concrete contracts because it is solid" and another wrote "concrete is a solid and doesn't shrink or expand." Additionally, 21% (12 students) circled "Not Sure" or did not choose any answer choice. These results are consistent with the results of the frying pan item that asks students to predict the macroscopic behavior of a solid object.

Thermometer item. For the thermometer item, students were asked to *explain* why the liquid in a thermometer expanded when placed in hot water. The answer choices all offered molecular level explanations for the phenomenon of liquid expanding when heated. The item differed from the concrete sidewalk item and version 2 of the frying pan item in that students were asked to provide an explanation for a phenomenon in terms of the behavior of atoms and molecules, but they were not expected to make a prediction about what would happen when something was heated or cooled. Also, the substance whose behavior they were to explain was a liquid rather than a solid. More students got this item correct (36%) than got either the concrete sidewalk item (19%) or version 2 of the frying pan item (13%) correct, both of which expected students to predict the behavior of a solid object (see table 3).

Plastic bottle item. For the plastic bottle item, students were asked to *explain* why a plastic bottle full of air collapses when the temperature decreases. The answer choices all offered molecular level explanations (i.e., all the molecules of air left the bottle, the molecules of air got closer together, heat molecules escaped from the bottle, and the molecules of air broke down into atoms). Only a small number of students selected the distractors having to do with either water molecules or heat molecules leaving the bottle (because, as they said, the cap was on so nothing would escape). A small number chose the distractor that said the molecules would break down into atoms, and about a third of the students were unsure of what the correct answer was. As in the thermometer item, students were asked to explain a phenomenon, not make a prediction of what would happen. This item differed from the others in that the material that was contracting was a gas, not a liquid or solid. On this item, 42% answered correctly (see table 3).

Table 3. Percent correct by type of item for thermal expansion and contraction items.

Item	State of Matter	Macro phenomenon/Atoms and Molecules	Prediction or Explanation	n	% Correct
Frying Pan Version 1	Solid	Atoms/Molecules only	Prediction	32	56%
Plastic Bottle	Gas	Atoms/Molecules plus Macro	Explanation	57	42%
Liquid in a thermometer	Liquid	Atoms/Molecules plus Macro	Explanation	56	36%
Concrete sidewalk	Solid	Macro only	Prediction	57	19%
Frying Pan Version 2	Solid	Atoms/Molecules plus Macro	Prediction	30	13%

Table 4. Percent correct by type of item for motion of atoms and molecules items.

Item	State of Matter	n	% Correct
If temperature of a substance increases, average speed of atoms/molecules increases.	All states	58	74%
Average speed of molecules of a liquid stays the same if temperature is constant.	Liquid	53	56%
Molecules of water are always in motion.	Liquid	55	47%
Molecules of solid glass are always in motion.	Solid	57	41%

Student responses to items having to do with the motion of atoms show that most students knew that the average speed of the atoms/molecules of a substance increases as the temperature increases. Fewer students knew that the atoms/molecules of a liquid and solid are always in motion (see table 4).

Gender comparisons. Finally, the performance of female students and male students was compared. The percent of male and female students who responded correctly to each item are shown in table 5 along with the results from an independent samples t test. Comparisons of means indicate that there are no significant gender differences in the percent correct for any of the items. The only items that approached significance when boys and girls were compared are the frying pan items. For the two frying pan items combined, 27% of the girls answered correctly and 50% of the boys answered correctly (t= -1.846, p=0.07), suggesting that girls may be slightly less likely to believe that a frying pan shrinks when cooled.

Table 5: Number and percent correct for all of the items separated by gender.

Idea	Item	Female Students		Male Students		t	Sig. (2-tailed)
		%	n	%	n		
Thermal Expansion and Contraction	Iron Frying Pan (data from version 1 and 2 combined)	27%	37	50%	24	-1.846	0.070
	Concrete sidewalks	16%	37	21%	24	-0.451	0.653
	Bottle	38%	37	50%	24	-0.930	0.356
	Thermometer	32%	38	41%	22	-0.721	0.474
Motion of atoms	Water molecules	53%	34	38%	24	1.154	0.253
	Glass molecules	46%	37	33%	24	0.970	0.336
	Constant temperature	53%	36	62%	21	-0.661	0.512
	Increasing temperature	70%	37	80%	25	-0.850	0.399

Discussion

The key idea for thermal expansion specifies that students should be able to link the change in the distance between atoms or molecules to macroscopic phenomena of substances expanding or contracting. It is important for students to not only know what is happening at the molecular level but also to link those molecular level phenomena to the corresponding real world macroscopic events. The results of our pilot test have shown that this is a difficult task for middle to early high school students. We learned that 7^{th} – 9^{th} grade students can have a molecular level understanding of thermal expansion and contraction, and they can have a molecular level understanding of atoms and molecules in motion, but have difficulty applying that knowledge to corresponding macroscopic phenomena. Similar results have been found in studies examining students' knowledge of the states of matter and changes of state (Lee et al., 1993; Gopal et al., 2004; Nakhleh et al., 2006).

The two most difficult items for students were those that asked them to predict that a solid would expand when heated or contract when cooled. It appears that their beliefs about contraction or expansion of solids is more important to them when answering test questions than their knowledge that atoms or molecules of substances (including solids) get farther apart or closer together when heated or cooled. This is confirmed by the fact that students seem to have less difficulty with two items in which they were asked to *explain* phenomena that they were told happened, and presumably were things that were believable to them (i.e., liquid expanding and, therefore, rising in a thermometer, and a gas contracting inside a cooled bottle).

The results from version 1 of the frying pan item and two of the other items aligned to thermal expansion show that the majority of students could successfully identify the molecular level phenomenon that the distance between atoms changes with changes in temperature, and that they were able to use this idea to explain phenomena that they were told have occurred (i.e., liquid in a thermometer expanding and a plastic bottle of air shrinking). However, the results from version 2 of the frying pan item and the concrete sidewalk item indicate that this knowledge is disconnected from the actual observable world in which the students live, at least when they are asked to make a prediction about something they probably have not seen happen. We want students to understand what happens on the molecular level, but we also want students to know that these molecular level phenomena are directly linked to events that occur in their observable world.

Implications for assessment design. We have gained a number of insights from our pilot testing of these items that we have applied both to the revision of the test items and to the revision of our expectations for students. First, we are revising the frying pan item (and others like it) to make the answer choices to the macroscopic level item (version 2) as plausible as possible. It may be that students are focusing mainly on the macroscopic part of the answer choices without giving much thought to the molecular explanation. One possible item revision would be to foreground the molecular level phenomenon by placing it before the macroscopic phenomena in each answer choice. The correct answer choice would then say: *The distance between iron atoms decreases so the pan gets a tiny bit smaller.*

Also, from the students' responses to the concrete sidewalk item, we discovered that many students believe that solid substances cannot change size with changes in temperature. The original frying pan item did not have an answer choice that addressed this misconception. In the revised version we will add an answer choice in which the pan remains the same size to get additional confirmation concerning this misconception.

Originally, the phrase "even though you cannot see/feel it" was not part of the answer choices for version 2 of the frying pan item. The phrase was added after we conducted think-aloud interviews. The students who were interviewed felt that none of the answer choices were plausible based on their everyday experiences with heating and cooling frying pans. We thought that adding the phrase would make the answer choices more plausible. Still, only 13% of students answered this item correctly even when they were told that the change in size was too small to be seen. It may be that the students' actual experiences with the world may be so powerful that such minor revisions to the items are not enough to change how they respond. For some of these ideas, it is likely that the only thing that will change what students think is quality instruction that provides students with visual evidence of thermal expansion and contraction.

We also added a sentence to our clarification statement that says: *Students are expected to know that expansion or contraction due to changes in temperature is not permanent (e.g., objects that expand when heated then contract when cooled).* This is in response to the students who thought that a frying pan that gets smaller when cooled would eventually disappear if you cooled it enough times.

Pilot testing also confirms that slight differences in the stem and answer choices of multiple choice questions can have significant effects on how students respond, especially when their knowledge is developing and still insecure. This supports the idea that a single test item is not sufficient to measure student understanding of science ideas. Although our goal is to be very precise in our alignment of test items to learning goals, even the level of precision that we achieve still leaves open the possibility of variation in what students are asked to do with their knowledge and in what contexts. In the set of five thermal expansion/contraction items that we discussed in this paper, we have some items that ask students to explain phenomena and others that ask them to predict phenomena; some items ask about the behavior of gases, some about liquids, and some about solids; some items ask students about thermal expansion and others about thermal contraction; and we have some items that ask students what is happening at the atomic/molecular level, some at the macroscopic level, and others that ask them to link the macroscopic phenomena to the atomic/molecular phenomena. Although, to many assessment developers, alignment is achieved when there is a match between test items and a general topic area, it is clear that to really probe student understanding, a much finer analysis of the structure of test items is needed.

Conclusions

Pilot testing is a valuable tool that provides information about students' content knowledge and about the comprehensibility of assessment items. For the items discussed here, we have learned that some students hold misconceptions about the mass, size, and number of atoms when the temperature of a substance changes. We have also learned that students have difficulty applying their knowledge of the atomic/molecular phenomena to corresponding macroscopic phenomena. Based on these findings, we were able to use the pilot test as a way of informing assessment item design and the expectations we have for students.

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