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Helping Students Revise Disruptive Experientially Supported Ideas about Thermodynamics: Computer Visualizations and Tactile Models

Douglas Clark,[1] Doris Jorde[2]

[1]*College of Education, Division of Curriculum and Instruction, Arizona State University, Tempe, Arizona 85287-0911*

[2]*Department of Teacher Education and School Development, University of Oslo, P.b. 1099 Blindern, 0317 Oslo, Norway*

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Abstract: This study analyzes the impact of an integrated sensory model within a thermal equilibrium visualization. We hypothesized that this intervention would not only help students revise their disruptive experientially supported ideas about why objects feel hot or cold, but also increase their understanding of thermal equilibrium. The analysis synthesizes test data and interviews to measure the impact of this strategy. Results show that students in the experimental tactile group significantly outperform their control group counterparts on posttests and delayed posttests, not only on tactile explanations, but also on thermal equilibrium explanations. Interview transcripts of experimental and control group students corroborate these findings. Discussion addresses improving the tactile model as well as application of the strategy to other science topics. The discussion also considers possible incorporation of actual kinetic or thermal haptic feedback to reinforce the current audio and visual feedback of the visualization. This research builds on the conceptual change literature about the nature and role of students' experientially supported ideas as well as our understanding of curriculum and visualization design to support students in learning about thermodynamics, a science topic on which students perform poorly as shown by the National Assessment of Educational Progress (NAEP) and Third International Mathematics and Science Study (TIMSS) studies. © 2003 Wiley Periodicals, Inc. J Res Sci Teach 41: 1–23, 2004

This study explores the question of whether we can facilitate students' understanding and acceptance of thermal equilibrium by helping them revise their experientially supported ideas about why objects feel the way they do. We hypothesized that integrating a tactile model into an existing thermal equilibrium visualization would not only help students revise their understanding of why objects feel the way they do, but also help students connect these revised ideas to instructed ideas about thermal equilibrium and thus increase their understanding of thermal equilibrium.

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Correspondence to: D. Clark; E-mail: dbc@asu.edu
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Student Learning in Thermodynamics

Thermodynamics is a topic area that the research literature considers challenging and age appropriate for the eighth-grade students of this study. Students clearly hold many intuitive ideas about heat (Clough & Driver, 1985; Erickson, 1979; Erickson & Tiberghien, 1985), and everyday experiences form the basis for these ideas. These ideas often involve predominantly substance-based conceptions. Everyday, children are exposed to the colloquial term *heat* as a noun, verb, adverb, and adjective, and these multiple uses may lead to confusion (Erickson & Tiberghien, 1985). Even high school students have great difficulty with energy concepts, the particle model, and the distinction between heat and temperature (Kesidou & Duit, 1993). Furthermore, these concepts are also challenging to scientists, who may make more accurate predictions than students, but who also have difficulty explaining everyday phenomena in interviews (Lewis, 1996; Lewis & Linn, 1994), and who maintain divergent representations in their writing (Tarsitani & Vicentini, 1996).

Heating concepts develop more rapidly than cooling concepts, and patterns of incorporating heating and cooling concepts are similar across cultures (Slone, Tredoux, & Bokhorst, 1996), suggesting that domain-specific knowledge is involved in understanding these concepts. Familial and cultural experience, however, also appear to influence students' development of conceptual understanding (Jones, Carter, & Rua, 2000). Some researchers claim that students' concept development often parallels historical development of the same concepts (Wiser, 1995; Wiser & Carey, 1983). Other researchers take more Piagetian views of the development of these concepts, proposing maps of heat concepts through which children develop chronologically (Albert, 1978; Shayer & Wylam, 1981). Our current study continues exploring the relationship between students' experientially supported ideas and students' formation of a normative understanding of thermodynamics.

Although the broader conceptual change literature obviously informs this study, less is known specifically about conceptual change in thermodynamics. Much research catalogues students' alternative conceptions about instructed science ideas (e.g., Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Duck, & Wood-Robinson, 1994; Gunstone, 1987; Gunstone & White; 1981; Hestenes, Wells, & Swackhammer, 1992; Novak, 1987; Wandersee, Mintzes, & Novak, 1994). Other work focuses on helping students build understanding of the scientifically normative versions of instructed ideas, such as bridging analogies (Brown & Clement, 1989; Clement, 1988, 1993), benchmark lessons (Hunt & Minstrell, 1994; diSessa & Minstrell, 1994), and instructional conversations and wait time (Rowe, 1974, 1991). Research of this sort most relevant to our current study focuses on self-explanation (Chi, 1996; Chi, Bassok, Lewis, Reimann, & Glaser, 1989), discrepant events (e.g., Appleton, 1995; Wright & Govindarajan, 1992, 1995), "worked" examples (Ward & Sweller, 1990), and pivotal cases (Linn, in press). As discussed in the following sections, this study synthesizes the findings and ideas from these areas of research to target students' experientially based ideas that are tangential but disruptive to instructed ideas. By first helping students revise their experientially disruptive ideas and then helping students connect these revised ideas to the instructed ideas, we increase student understanding of thermal equilibrium on posttests, delayed posttests, and interviews.

Research Context

The current study takes place within a semesterlong computer-mediated curriculum focusing heavily on thermodynamics and other energy topics (Linn & Hsi, 2000). In particular, this research focuses on a thermal equilibrium visualization embedded within a weeklong thermal equilibrium inquiry project called Probing Your Surroundings. Within the curriculum, students use computers as they design experiments, predict outcomes, collect data in real time, design visualizations, display results, record observations, and prepare analyses.

In pilot work, Clark (2000, 2001) analyzed students' learning about thermal equilibrium and the role of experientially supported ideas. Clark (2000, 2001) mapped the facets and connections embedded in student explanations in the case study interviews across their eighth-grade semester and into high school. These maps focus on students' knowledge integration, including many situations where students' experientially supported ideas conflict with their integration of instructed thermodynamics ideas.

In our current study we focus on the strong connection between students' experiential knowledge about how objects feel and the students' understanding of thermal equilibrium. Thermal equilibrium is a challenging physical science concept that is central to the National Science Standards for middle school students (NRC, 1996). Thermal equilibrium, as a concept, explains aspects of heat energy transfer between objects of different temperatures. Essentially, objects in the same environment (e.g., in a refrigerator) will eventually become the same temperature unless they produce their own heat energy. For example, a wooden bowl and a metal spoon become the same temperature as the refrigerator, but a living person does not become the same temperature. This is because there is a net heat energy flow from objects of higher temperatures into objects of lower temperatures until equilibrium is established.

Thermal equilibrium is a difficult concept for students because of their personal experiences. Some materials usually feel hotter or colder than other materials. For example, a metal spoon in the refrigerator will feel colder than a wooden bowl even though after several hours in the refrigerator they are the same temperature. Certain materials, such as metal and glass, tend to feel hotter or colder than other materials, such as wood, because they conduct heat energy better. For example, heat energy flows more quickly out of your warm hand when you touch a metal spoon in the refrigerator than when you touch a wooden bowl. Students, however, interpret this experience to mean that the metal spoon is actually a lower temperature than the wooden bowl because "if it feels different it must be a different temperature." Students are so committed to this interpretation of their experience that they are extremely resistant to the idea that the objects actually become the same temperature.

Computer Visualizations and Tactile Models: Developing a Strategy to Help Students Revise Disruptive Experientially Supported Ideas

Based on the pilot longitudinal case studies (Clark, 2000, 2001) we hypothesized that students would make significant progress in integrating normative school ideas about thermal equilibrium if we could help students revise their disruptive experientially supported tactile ideas. We approach this strategy through a thermal equilibrium visualization that incorporates a tactile model through which students can investigate why objects feel hot or cold while investigating thermal equilibrium. Our goal is to scaffold the students in revising their understanding of why objects feel the way the do so as to support rather than disrupt the instructed thermal equilibrium ideas. Such a revision allows a better fit between students' experientially supported ideas and instructed ideas so that students can make sense of their everyday experiences.

We provide traditional visual and audio feedback within the computer visualization rather than kinetic or thermal haptic feedback because we want to use promising technology that is relatively available in classrooms. The visualization therefore incorporates a tactile model in the sense that it models why objects feel hot or cold, not in the sense of incorporating haptic feedback.

Computer visualizations are the vehicle based on their capacity to support the creation and integration of intermediate mental models within the curriculum (Lewis, Stern, & Linn, 1993; Linn & Hsi, 2000; White, 1993a, 1993b).

Visualizations and animations are more effective than diagrams in supporting students' identification of ''natural behavior'' and causal relationships (Kaiser, Proffit, Whelan, & Hecht, 1992; Michotte, 1963). As students work with a visualization, they can depict and parse the causal relation between the objects within the visualization and create a mental model (White, 1993a). All of these ideas suggest that a visualization environment holds promise for helping students revise their understanding of why objects feel the way do and revise the connections between thermal equilibrium and tactile ideas.

Although some visualizations have shown promise, not all visualizations are effective [e.g., reviews by Park and Hopkins (1993) and Rieber (1990)]. The literature suggests that visualizations should make normally tacit behavior visible (Norman, 1990; Merrill & Reiser, 1993, 1994) and should clearly explain causality (Faraday & Sutcliffe, 1997). In addition, cognitive load theory (Sweller, 1993, Chandler & Sweller, 1991, Ward & Sweller, 1990) suggests that eliminating unnecessary cognitive tasks improves learning. Furthermore, Scaife and Rogers (1996) suggested that effective visualizations can (a) facilitate cognitive offloading by providing students with an ''external cognitive aid'' to reduce the amount of information that needs to be held in working memory while building connections, (b) re-represent problems in a format that facilitates the solutions, and (c) graphically constrain the types of mental models a student could construct. To be effective, visualizations should be embedded in a curriculum that focuses students on the connections and ideas within the visualization (Raghavan & Glaser, 1995; Snir, Smith, & Grosslight, 1993; White, 1993a). In addition, visualizations that provide an instructional format with explicit learning objectives and structure result in active engagement of the learner, leading to higher motivation and better integration and retention of content (Naps, 1996; Hansen, Scrimpsher, & Narayanan, 1998).

To support students' revision of tactile ideas and connections to thermal equilibrium, we organize the visualization activities in our current research around a series of discrepant events focusing on tactile and thermal equilibrium ideas in an everyday context. Discrepant events are phenomena that occur in a way seemingly contrary to initial reasoning, and the exploration of discrepant events has been shown effective in supporting conceptual reorganization (e.g., Appleton, 1995; Potthoff, Yeotis, Butel, Smith, & Williams, 1996; Wright, 1981; Wright & Govindarajan, 1992, 1995). Our implementation follows (a) Linn's (in press) ''pivotal case'' focus on everyday examples, (b) Brown and Hershberger's (1998) recommendation focusing on examples that illustrate special cases of an idea, and (c) Ward and Sweller's (1990) findings that ''worked'' examples are more effective as learning tools than traditional problems because they focus attention on the salient aspects of the problem while imposing a light cognitive load on the learner.

Our goal in the visualization is to support conceptual reorganization by providing a context or example that highlights contradictions or shortcomings resulting from the original intuitive idea and promotes an alternative dimension or idea. In this way, we hope to make more visible the problematic aspects of students' current tactile ideas. Simultaneously, we also want to make the utility of the new dimension or idea more accessible and comprehensible. Through the visualization, we hope to support reorganization of the students' ideas toward a more coherent and nuanced view of thermodynamics.

We present these discrepant events about temperatures and ''feels'' of objects in the everyday context of a story about a metal table and a wood chair left in a hot car trunk. Students first investigate the temperature of the objects and how they might feel in the trunk and then in the house several hours after being brought inside. Students are challenged by the activity to reconcile the fact that wood and metal objects can be the same temperature but feel different. We chose an everyday context based on findings that demonstrate that visualizations can be conceptually enhanced to promote knowledge integration by directly connecting concrete familiar objects with abstract science models and concepts (e.g., Linn, in press; Snir et al., 1993). We also chose an everyday context based on Norman's (1990) findings that leveraging physical analogies and culturally relevant examples leads to more immediate understanding and findings that students need to integrate visualizations with their existing models to support lasting impact on their understanding (Foley, 2000; Lewis et al., 1993; Linn & Hsi, 2000).

In addition to the advantages of visualizations discussed in the literature, Clark's (2000, 2001) pilot longitudinal studies demonstrate multiple examples where inevitable experimental error in hands-on temperature measurements supports students' nonnormative ideas that metal and wood objects only ''come close'' to being the same temperature because of thermal equilibrium but remain different temperatures and thus feel different. For the current study, we expected visualizations to provide students a clearer set of data with which to revise their connection between objects' temperatures and how objects feel because the visualization could be programmed to omit experimental error. Clark's (2000, 2001) pilot longitudinal studies also suggested that visualizations might be an effective choice because the pilot studies demonstrate that students warrant their explanations with references to classroom visualizations more often than with references to any other classroom activity in the curriculum.

The Visualization and Its Curricular Context: The Probing Your Surroundings Project

The current study implements the computer visualization within the 5-day (5 class period) Probing Your Surroundings project about thermal equilibrium. The Probing project uses WISE[1] (Web-Based Inquiry Science Environment) Internet software with custom laboratory, electronic peer critique, and visualization modeling components to support students as they investigate thermal equilibrium.

Students start the Probing project by making predictions about the temperatures of everyday objects around them in the classroom. Students then use thermal probes to investigate the temperature of each of these objects and construct principles that describe the patterns encountered. This first portion of the Probing project attempts to cue students' conflicting ideas. In particular, Probing focuses on students' sense that objects are different temperatures because they feel that way, and students' instructed idea that objects in the room should become the temperature of the room. The software then places students in electronic discussion groups, allowing students to critique each other's principles. As part of this process, the students are required to support their assertions and claims with evidence from their labs and other experiences.

After the discussions, the students experiment with the visualization. The visualization activities take approximately 1 of the 5 class periods devoted to the Probing project (or approximately 55 minutes out of the total 275 minutes). The visualization focuses on metal and wood objects left in the trunk of a car on a hot summer day. Our current research compares two versions of the visualization. The first version presents the core thermal equilibrium model that allows students to experiment with the relationship between thermal equilibrium and conductivity. The second, tactile version has a sensory model integrated with the core thermal equilibrium model to allow students to connect ideas about how objects feel to their experimentation. The first version was presented to the control group and the second version was presented to the experimental group.

The Core Visualization Experienced by All Students

Students begin the visualization activity by reading the background story about objects in a hot car trunk. In the story, students are asked to imagine going to a hardware store on a hot summer day and buying a wood chair and a metal table. The chair and table are left in the trunk for 3 hours while the students are doing other errands. During this time sun has been beating down on the car, and the trunk gets hot. After several hours in the hot car trunk, the hot wood chair and metal table are brought into the house. When finished reading the story, students interact with the visualization through several steps:

1. Students first write predictions about the temperature and feel of the objects left in the trunk for several hours.
2. Students then write predictions about the feel and temperature of the objects after the objects have been brought inside the house overnight.
3. After writing their predictions, the students follow an introductory tour explaining the visualization environment.
4. After the predictions and the tour, students recreate the trunk-into-house story using the visualization.

The visualization shows students the rate of heat flow and temperature change of the objects over time as they conduct their investigation.

The visualization is conceptually enhanced (Snir et al., 1993), connecting the abstract model of normally invisible heat flow as visible arrows to the concrete objects and context of metal and wood furniture in a hot car trunk (Figure 1). Temperature is represented by a grayscale continuum with darker shades denoting higher temperatures. This color scale is visually represented in a scale on the left side of the screen. The objects' information tags numerically display the temperature and conductivity of each object. In the visualization, the size of the animated red arrows leaving or entering an object represents the rate and direction of heat flow into or out of the object. Larger arrows represent a larger rate of heat flow.

Students may run the visualization repeatedly. Students can change environmental attributes using the tools at the top of the screen. Using these tools, students can add new objects, vary the temperature of the room and objects, and vary the conductivities of the objects. After the

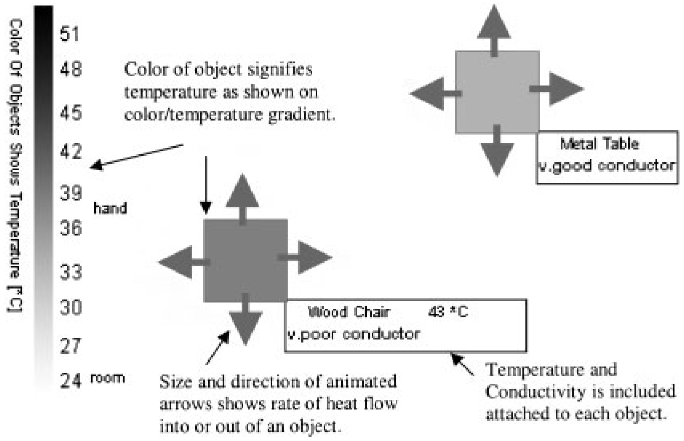


Figure 1. Core visualization experienced by students in both control and experimental groups.

visualization, students answer questions regarding their predicted and actual outcomes as well as write explanations for what they have observed. Watching the visualization allows students to observe that objects eventually reach the same temperature as their surroundings.

Augmented Visualization for Experimental Group

Students in the experimental tactile group had the additional opportunity to click on an object to see how it feels. This integrated tactile model shows a hand next to the object at the base of the screen with the same heat flow arrows flowing to or from the hand depending on the temperature gradient between the hand and object. Higher rates of heat flow (per unit of surface area) between the object and the hand determine how hot or cold the object feels. As with studies demonstrating the efficacy of sound narration in reinforcing information (Baecker, 1998; Baecker et al., 1997; Faraday & Sutcliffe, 1997), the visualization provides the students with audio and text messages describing how the object feels (e.g., ''This feels burning hot!''). This tactile model is integrated into the experimental group's notes where, in addition to making predictions and explanations regarding temperature, the students also make predictions and explanations for why objects feel the way they do.

In addition, the experimental group received a second screen (Figure 2) with three cold objects (10°C) and three hot objects (80°C) of different conductivities. Students can only feel the objects and cannot run this screen as a thermal equilibrium simulation over time. The goals of this second screen include: (a) re-representing (Scaife & Rogers, 1996) the problem in a format that facilitates the connection of conductivity to why objects feel the way they do, and (b) graphically constraining (Scaife & Rogers, 1996) the type of mental models a student can construct from the visualization so that they build a mental model connecting the instructed thermal equilibrium and insulation/conduction ideas to their experiential knowledge.

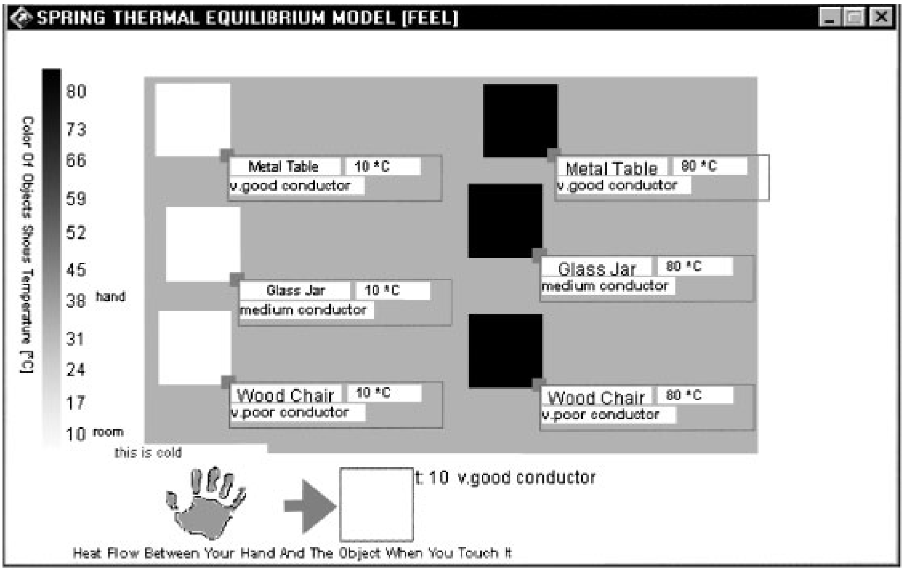


Figure 2. Supplemental tactile model component of visualization experienced by experimental group.

Methodology

One hundred twenty students in four classes of eighth-grade students complete the Probing project with these visualizations during one semester under the supervision of an experienced teacher who has worked extensively with the researchers. The school is located in a diverse Californian setting with an even distribution of boys and girls. The classes are typical eighth-grade physical science classes, labeled neither "honors" nor "remedial." Experimental groups for the study include: (a) 60 students in two classes exploring the visualization including the tactile model, and (b) 60 students in two classes exploring the control condition of the visualization without the tactile model. Classes were assigned randomly to each condition. Both conditions include all of the core components of the Probing project, including the lab, discussion, and core thermal equilibrium visualization. The only difference between the groups is that the visualizations in the experimental condition include the integrated tactile model.

The integration of the tactile model and the addition of the second tactile screen added only 15–20 minutes to the experimental group's visualization time. In total, the experimental groups spent approximately 65 minutes working with the visualization out of the 5 hours devoted to the Probing project. The control group had the option of spending additional time on the visualizations but generally spent approximately 45 minutes on the visualization and used the additional 15–20 minutes returning to the electronic discussions and pursuing additional review and reflection at the end of the project. The Probing project begins during the 8th week of the regular thermodynamics curriculum after the students have studied heat flow, the differentiation of heat and temperature, and insulation/conduction. Students' understanding of thermal equilibrium was assessed for this study through a pretest immediately before the Probing project and a posttest immediately after the project. After the posttest, the students completed another equilibrium lab, two projects on light, an integration project involving the design of the passive solar house, and an earthquake project. At the completion of this additional curriculum, 6 weeks after the Probing project, students were given a delayed posttest as part of their semester final exam.

To add insight to the test scores, interviews were conducted with students and their partners in each class. They were chosen from the middle third of their class as determined by their performance on the project pretest. Interviews were conducted after both the pretest and posttest. The six interview questions expand on the test questions, probing students' understanding of thermodynamics in the context of everyday situations (see Appendix B). Their purposes are to determine students' understanding and to identify contradictions, integrations, differentiations, and reasonings. Interview questions were developed through prior work with the curriculum (Linn & Hsi, 2000). Two raters categorized the interview responses in terms of the visualization and its role in the students' explanations. During the visualization component of the project, interview students were also videotaped with their partners.

Tests and Analyses

The pretest, posttest, and delayed posttest all contain 4 questions analyzing students' understanding of thermal equilibrium, 1 question investigating students' understanding of why objects feel the way they do, and 5 control questions focusing on other thermodynamics topics. These 5 control questions are included to establish that the experimental and control groups are comparable in their understanding of other areas of thermodynamics. These 10 questions have been developed through earlier work with the curriculum (Linn & Hsi, 2000). In addition, 2 novel thermal equilibrium and tactile questions are included on the delayed posttest to measure students' understanding of thermal equilibrium and why objects feel the way they do in novel settings as opposed to using questions that the students have seen twice before (See Appendix B for text of the thermal equilibrium and tactile questions).

Students mean scores are compared across experimental groups through analysis of variance. Reliability of the questions comprising the thermal equilibrium score is measured using a Cronbach alpha reliability test. The interviews and videotapes are used to provide insight into the nature of the impact of the visualization.

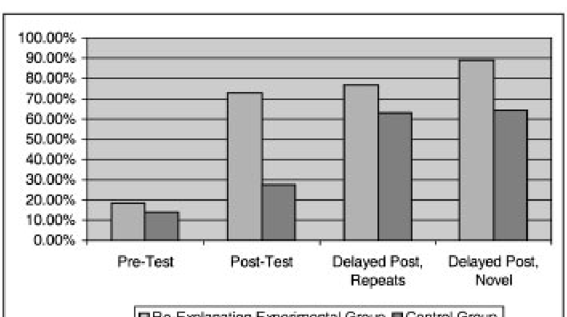
Results and Analysis

We hypothesized that (a) the visualization with the tactile model would help students revise their experientially supported knowledge of why objects feel hot or cold, and (b) engaging in this process would result in an improved understanding of the instructed thermal equilibrium ideas.

Revising Disruptive Experiential Tactile Ideas of Why Objects Feel Hot or Cold

There is no significant difference between the experimental and control groups on the pretest tactile question measuring why objects feel the way they do (Appendix A, Question 1). After completing the Probing project, however, students in the experimental tactile group perform significantly better on this same question, $F(1, 100) = 26.1$, $p < .0001$) (Figure 3).

Eight weeks later on the delayed posttest, we see that the control group has closed the gap on the repeated tactile question, but the experimental group continues to demonstrate a significantly higher mean understanding of why objects feel the way they do in their explanations on the novel tactile questions, $F(1, 99) = 9.7$, $p = .002$ (Figure 3 and Questions 6a and 7a). From these results we can conclude that the enhanced visualization successfully increases student understanding of why objects feel the way they do. Furthermore, this understanding remains strong on the delayed posttest, suggesting that the understanding is durable. These findings therefore validate the first



Delayed Post-Test Challenge Questions: F(1, 99) = 9.7, p = 0.002

Delayed Post-Test Repeated Questions: not significant

Post-Test: F(1, 100) = 26.1, p < 0.0001

Pre-Test: not significant

Text of Sample Delayed Posttest Novel Question: Imagine you have a metal bowl that is 47°C and a wood bowl that is 47°C (47°C is ten degrees warmer than your body temperature.) Do they feel the same, does the metal one feel hotter, or does the wood one feel hotter? (check one)

____ They feel the same
____ The metal bowl feels hotter
____ The wood bowl feels hotter

What is the **main reason** for your answer?

Figure 3. Performance on tactile measures by control and re-explanation groups over time through the delayed posttest.

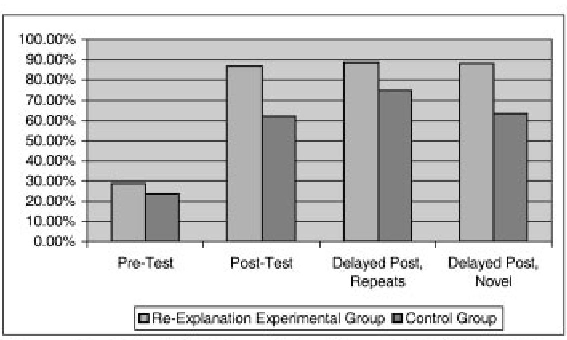
part of the hypothesis that working with the visualization incorporating the tactile model can help students revise their experientially supported ideas of why objects feel the way they do.

Because this is a comparison of tactile versus nontactile visualizations, this finding is not entirely surprising, but it is still impressive that a 15-minute extension to a computer visualization can have so profound an effect within a 10-week thermodynamics curriculum, even on a delayed posttest 6 weeks later. In terms of this study, the finding is also important because it supports the first claim of the hypothesis that we can help students revise their experientially supported tactile ideas. An important question is whether this revision of the students' tactile ideas also results in better performance on the combined thermal equilibrium measures (Questions 2, 3, 4, 5, 6b, and 7b) for which the control and experimental groups received the same visualization models.

Students' Understanding of Thermal Equilibrium

According to the second part of the hypothesis, increasing students' understanding of why objects feel the way they do should also improve students' understanding of thermal equilibrium in general. The combined measure of thermal equilibrium understanding includes four questions (Appendix A, Questions 2–5). The experimental and control groups show no significant differences on the pretest for this combined thermal equilibrium measure, but on the posttest the experimental group performs significantly better than the control group, $F(1, 100) = 7.7, p = .007$) (Figure 4). Given that the only difference in instruction involves the inclusion of the tactile model, this result is impressive and supports the hypothesis that revising students' experientially supported tactile ideas is critical to helping them understand instructed ideas about thermal equilibrium.

On the combined measure results for the delayed posttest, as on the tactile knowledge item, students in the control group narrow the gap on the repeated questions, but the experimental group



Delayed Post-Test Challenge Questions: F(1, 97) = 6.93, p = .010

Delayed Post-Test Repeated Questions: not significant

Post-Test Questions: F(1, 100) = 7.7, p = .007

Pre-Test Questions: not significant

Sample Delayed Post-Test Novel Question:
Imagine you have a metal bowl that is 0°C and a wood bowl that is 0°C (0°C is the temperature at which water freezes). Imagine that you bring them into a 23°C room. (23°C is a normal room temperature)
What temperature will the wood and metal bowls be after 24 hours?
Temperature of metal bowl after 24 hours = ____ °C
Temperature of wood bowl after 24 hours = ____ °C
What is the main reason for the temperatures you predicted for the wood and metal bowls?

Figure 4. Performance on thermal equilibrium measures by control and re-explanation groups over time.

continues significantly to outperform the control group on the novel questions (Questions 6b and 7b) about thermal equilibrium, $F(1, 97) = 12.4$, $p = .001$) (Figure 4). This outcome supports the second part of the hypothesis that targeting the revision of students' experiential knowledge about why objects feel the way they do is critical to improving students' understanding of thermal equilibrium.

Additional Statistics and Issues

The only outcome measure that in any way contradicts our interpretation of the findings involves 1 of the 4 thermal equilibrium questions on the pretest. Whereas the combined measure of the four thermal equilibrium questions (Questions 2–5) shows no significant pretest differences overall, performance on Question 5 on its own is significantly different between the experimental and control groups on the pretest, $F(1, 100) = 7.5$, $p = .007$). The students first encounter Question 5 on the project pretest. We therefore cannot look earlier in the semester for differences on this question, but we can show that: (a) there are no significant differences on the other three thermal equilibrium questions, the tactile question, or the other five baseline questions analyzing other thermodynamics topics, and (b) there is also no significant difference between groups on a semester pretest that was administered separately from this study as part of the normal curriculum.

To check that the items in the combined thermal equilibrium assessment measure the same understanding and topic, we conducted a Cronbach alpha reliability test of the four questions in the combined thermal equilibrium measure. This test yields an α reliability coefficient of 0.395 on the pretest, 0.895 on the posttest, and 0.925 on the delayed posttest. These results suggest that (a) successful students on the posttest and delayed posttest have developed an integrated understanding of thermal equilibrium allowing them to perform well on all the questions, and (b) success on an individual project pretest question is relatively independent of success on other questions, suggesting that success on a pretest question relies more on context-dependent knowledge than on principled understanding. These results therefore suggest that the differing performance on the pretest questions is context dependent and not indicative of global differences between the groups. Because there are no other significant disparities between the groups on the pretest, and since the combined measures show significant disparities, we conclude that the groups are essentially equivalent.

In addition, along with the tactile and thermal equilibrium questions, students also answer five control questions focusing on other thermodynamics topics. As expected, there are no significant differences in mean student performance between control and experimental groups on the pretest, posttest, or delayed posttest for these five control questions focusing on other thermodynamics topics. The conformity on these five control questions supports the general equivalence of the experimental and control groups in terms of their understandings of other thermodynamics topics. This equivalence outcome for other thermodynamics topics highlights the success of the tactile strategy and intervention and its effect on students' understanding of thermal equilibrium. Because the groups remain equivalent in the control questions measuring understanding of thermodynamics topics not addressed by the visualizations, we assume that no outside global variable is responsible for the significantly stronger performance of the experimental group on the thermal equilibrium and tactile questions for the posttest and delayed posttest.

Insights from the Interviews

The statistical analyses show that whereas both control group and experimental group students make progress in their understanding of thermal equilibrium during the project, students in the experimental group make significantly more progress. What is the nature of this difference? To probe this question, we looked to the interviews, which provide insight into what students may or may not have learned using either the core visualization or the experimental tactile version. Chuck, Cedric, and Cynthia (pseudonyms) are students from the control group who work with the core version of the visualization that does not include the hand and integrated tactile model. Tom, Tanya, and Tabitha (pseudonyms) are students from the experimental tactile group who work with the version of the visualization that includes all the core elements as well as the integrated tactile model and hand. Through the comments of Tom and Chuck we first demonstrate that students understood the basic format of the visualization. Then we go discuss the impact of the core version of the visualization on the control group. Finally we highlight the importance of the integrated tactile model to the success of the experimental tactile group.

Efficacy of the Basic Visualization Design. The basic format of the visualization is comprehensible to students of both groups. When Tom is asked what he thinks about the visualization he explains that ‘‘the simulation was really cool cause you could see that the amount of heat that the heat arrows [represented], you could see how much heat was entering and how much was leaving. If there was a small arrow, obviously there was very little heat leaving. And it showed the heat dispersing into like other areas and stuff.’’ Furthermore, many students express enjoying the visualization. For example, Chuck said that he ‘‘found it a lot easier than the real-time because we didn’t have to get the equipment set up . . . actually I like simulations better.’’

Outcomes for the Control Group. For some students in the control group, the core visualization proves sufficient to help them with their understanding of thermal equilibrium. Students like Chuck come away with the basic idea that objects will become the same temperature in the same area after enough time ‘‘like when we did that [visualization] when we had like the metal table and the Styrofoam table, you would set up like with different degrees Celsius they would all end up the same way that you set it at.’’ Similarly, Cedric predicts that wood and metal will be the ‘‘same temperature’’ in the room. When Cedric is asked why one feels colder, however, he says, ‘‘Does it have something to do with the insulator . . . I have no idea.’’

Unfortunately, as shown in the statistics, many students in the control group still allow their experientially supported tactile ideas to dominate their thermal equilibrium predictions. We also see control group students, such as Cynthia, who have not successfully integrated their new school knowledge with their existing ideas. We see evidence of such experiential domination when Cynthia is asked to predict the temperatures of wool, wood, and metal objects in a cold ski cabin (5°C) where the furnace has been turned off for months. On the postinterview, Cynthia still predicts different temperatures for objects in a cold cabin, saying ‘‘wool sweater, 15 degrees, metal shovel, 5 degrees, wood table, 10 degrees. I chose this temperature because it made sense to me because wood and wool are insulators and metal is a conductor. There’s only a little heat, so loss of temperature would be the shovel, and then the wood and then the wool.’’ When further questioned about how she chose the temperature for the wool sweater, she adds that she ‘‘thought that would be the best insulator so . . . um . . . I figured that it would have the most heat in it.’’ When asked how they would feel, Cynthia explains that ‘‘the wool sweater would be kind of like . . . um . . . medium . . . it would be really cold but it wouldn’t be as cold as the other stuff . . . but the metal shovel would be like . . . really cold to touch and your fingers might stick to it . . . and the wood table would just be cold.’’ When asked why the objects feel that way, Cynthia says, ‘‘Um . . . well, out of experience . . . because I . . . had experience once . . . that’s basically what I felt.’’

Cynthia continues this line of thinking when asked how wood objects left in a hot car trunk would feel compared with metal objects. Cynthia explains that the wood object would ‘‘feel hot but it wouldn't burn you . . . because it's not as hot as the metal one.’’ Similarly in the context of metal and wooden spoons in a warm oven, Cynthia predicts that the ‘‘metal one would probably feel a little warmer than the wood one because [the wood one] doesn't have as much heat.’’

Thus, we see the same interaction of ideas demonstrated in Clark's (2000, 2001) pilot case studies: (a) the idea that metal acquires a more extreme temperature, (b) the idea that metal feels hotter or colder because it is hotter or colder, and (c) warrants involving convoluted twisted versions of classroom explanations, such as ‘‘the metal gets hotter because it conducts more heat.’’ Cynthia and other control group students have not worked with the integrated tactile model, and without this tactile component they have no basis for reconsidering the experiential knowledge that seems to disrupt their understanding of thermal equilibrium.

Outcomes for the Experimental Tactile Group. The experimental group works with the visualization that integrates the tactile model to graphically constrain and re-represent the problem to facilitate the revision of experiential knowledge. Reaction to the integrated tactile model is positive. As Tom explains, ‘‘There was a little hand thing you could press it . . . you could tell, it was just like being there. 'Cause you know how the senses, that the nerves send messages to your brain, this was just, like, you know you don't have nerves, they are on the computer and they automatically send it and your eyes receive it and send it to your brain, telling you that it is cold.’’

All of the experimental group postinterviews demonstrate the positive impact of the integrated tactile model. When Tanya is asked about the cabin question, she explains that the objects ‘‘will all be at room temperature.’’ When asked if ‘‘any of that information’’ came through the lab, she says, ‘‘Yes, the simulation with the hand helps a lot [because it shows] that different things that are the same temperature actually feel different.’’ This particular quotation raises the question of whether the students are acquiring a fact or an explanation. The posttest results, however, indicate that the experimental group is significantly more successful across multiple contexts. This suggests that the students are acquiring an understanding that they are able to apply more flexibly across contexts than a nominal fact might allow (diSessa, 1996).

Tabitha explains the positive impact of the visualization with the integrated tactile model even more clearly: ‘‘In my old labs I used to say that [the wood, wool, and metal objects in a cold cabin] would be different temperatures because how they conduct heat energy differently but now I think that they will be the same temperature but that they will feel different . . . they will all be around 5 degrees Celsius.’’ When asked what has convinced her, Tabitha says, ‘‘I think that it was the simulation. When they compared the glass, the wood and the metal all the same temperature and they felt differently when they were all at the exact same room temperature. The wood was kind of hot and the glass was really hot and the metal was so hot you could like burn your hand.’’

The improved understanding of why objects feel the way they do is not perfect for these experimental group students. Although these students have added the idea that ‘‘objects can be the same temperature but feel different,’’ they often do not include a clear mechanism in their explanations. For Tabitha, it is enough that the visualizations ‘‘prove that at the same temperature they feel different because they are made of a different material, like metal and wood are completely different.’’ When asked to explain why the objects feel hot or cold in terms of heat flow, Tabitha initially says that the metal object feels cold because ‘‘there is no heat flow into it or through it.’’ Apparently she has not fully integrated heat flow, insulation/conduction, and thermal equilibrium but is making progress in that direction. Proof of this progress is evident in how quickly she manages to integrate heat flow into her explanation in the ensuing discussion where she is able to explain that there is heat flowing "from your hand to the object . . . so if you hold [the cold metal] right here for a couple of minutes it will be warmer than it was before. Yeah, the heat is flowing into it."

Summary and Discussion

Results show that students in the experimental group significantly outperform control group students on the posttests and delayed posttests. This superior performance not only includes their tactile understandings, for which the experimental group receives the augmented visualization, but also their understanding of thermal equilibrium, for which the experimental and control group's receive the same visualization models. Interview transcripts of experimental and control group students corroborate these findings. Students in the experimental group demonstrate a greater ability to explain why objects feel the way they do, as well as to make normative predictions about the temperatures of objects in different surroundings.

More impressively, these results were achieved using only a prototype version of the visualization (Figure 1). After this study, the visualization has been improved extensively based on student interview data investigating the interface (Figure 5). The color scale has been changed from grayscale to red scale, which students connect with temperature more easily. The color/temperature key is now represented as a thermometer to make this connection even more

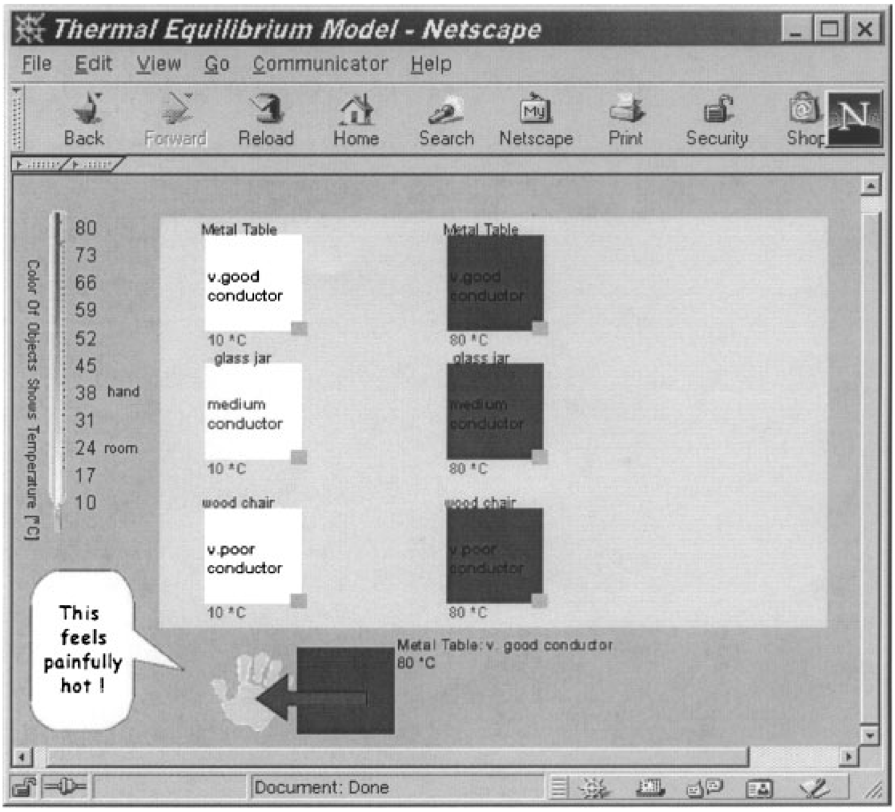


Figure 5. We revised the original simulation based on student outcomes and interviews.

accessible. The delivery and format of the messages about how an object feels have been enhanced using notations familiar to the students. The clarity of the connection of heat flow from hot to cold objects with regard to the hand has been enhanced by adjusting the positioning as well as by displaying the temperatures of the hand and object as text and color. Considering these improvements in clarity, transparency, and function, it seems probable that running this study again with the upgraded version of the visualization would achieve even more dramatic results.

Implications

The results from this study demonstrate the efficacy of incorporating sensory models into visualizations that specifically target students' experientially supported ideas that are disruptive to their integration of instructed ideas. These results are important for curriculum design because this strategy targets resistant misconceptions and can be integrated into curricula with minimal cost to schools and minimal training for students and teachers. The level of cost is low because: (a) the visualizations can be integrated into preexisting curricula as was done for this study, (b) these inquiry projects require minimal training of the teacher and students because the students are guided through each step by the computer while the teacher acts as a coach, and (c) the current version of the project can be accessed inexpensively because it requires only that the students have a current Web browser and so does not require schools to buy specific software or new equipment. The benefit is high for this low cost because misconceptions, such as the thermal equilibrium misconceptions addressed through this strategy, are well documented as being consistently difficult for students to revise (e.g., Driver et al., 1985, 1994; Gunstone, 1987; Gunstone & White; 1981; Hestenes et al., 1992; Novak, 1987; Wandersee et al., 1994).

In this study, we have applied our strategy only in the context of thermal equilibrium and why objects feel the way they do, but this strategy should be useful in other contexts beyond thermal equilibrium/tactile ideas. One such example would be the common idea students express about "warm wool," which disrupts their understanding of insulation and conduction. Many students have: (a) the experience that wool sweaters keep them warm, (b) the idea that wool is an insulator, and (c) the idea that heat does not flow easily through insulators. Using the second and third ideas, students should be able both to explain why the wool sweater keeps them warm and to predict what will happen when they wrap a cold object in wool. If experiential and target instructed ideas are not connected, however, students often give priority to their experiential knowledge that wool sweaters keep them warm, assuming that wool "makes things warm" and predicting that wrapping a cold soda in wool will make the soda warmer. Students make related assumptions about aluminum foil and several other materials. By helping students revise their experiential knowledge for why wool keeps them warm, we could use their experiential knowledge to support the target-instructed ideas for insulation and conduction.

This strategy should apply in other domains as well, but it will require in-depth longitudinal work to identify disruptive experientially supported ideas suitable for revision in these domains. In applying the strategy, we need not only to help students revise disruptive experiential knowledge but also to help students focus on the critical connections, as demonstrated when the pilot case study students pursue idiosyncratic explanations (Clark, 2000, 2001).

Next Steps

We believe that further emphasis on the biological aspect of the project might help students make even more progress in the future. Students in the experimental group tended to make the connection that conductivity affects rate of heat flow as well as how hot or cold an object feels, but for many of the students, their explanation and understanding of why objects actually feel the way they do would benefit from more depth. The current tactile model explains the differences in sensation solely in terms of rate of heat flow into or out of the hand. In some ways this tactile model is just another representation of the thermal equilibrium process, connecting the concepts directly to the human body. Emphasizing biological aspects, such as the fact that students are producers of heat, or focusing on how humans sense coldness in their fingers as a result of this heat flow might facilitate even stronger connections between physics, biology, and the students' experiential knowledge.

Another area for future investigation would involve the incorporation of actual kinetic or thermal haptic feedback devices into the simulation (e.g., Bussell, 2001; Jeong, 2001). Such kinetic haptic feedback capabilities are now becoming more common for video game consoles (e.g., the joystick vibrates when the car goes over gravel), and thermal haptic devices would be relatively simple to manufacture. Such haptic feedback would make the tactile model truly tactile. The problem for education is that such specialized equipment is unlikely to become widely available in classrooms. Nonetheless, it would be interesting to explore the effect of kinetic haptic feedback. For the current tactile model, the mouse might vibrate more quickly for larger rates of heat flow between the hand and the object. This kinetic feedback might also provide a useful starting point for discussing the molecular kinetic basis of heat and temperature. Similarly, incorporating a thermal haptic device that actually became warmer depending on the rate of heat flow between the hand and the object might scaffold students more directly and effectively. Helping students understand how this feedback relates to cold objects might prove difficult (e.g., slower vibration representing heat flow out of the hand might prove conceptually difficult for students) but would certainly provide interesting data.

Conclusions

In this study we incorporate a model of thermal sensation into a thermal equilibrium computer visualization to help students revise disruptive experientially supported ideas about thermal equilibrium. Our goal is to support understanding of instructed thermodynamics ideas which have traditionally proven challenging for students. Although the tactile intervention is not complex, the fact remains that thermodynamics instruction has been studied extensively (e.g., Albert, 1978; Clough & Driver, 1985; Erickson, 1979; Erickson & Tiberghien, 1985; Jones et al., 2000; Kesidou & Duit, 1993; Lewis, 1996; Linn & Hsi, 2000; Shayer & Wylam, 1981; Slone et al., 1996; Wiser, 1995), and yet the critical nature of this intervention had not been isolated. Thus, our results underscore the efficacy of the pilot longitudinal case study work's identification of strategies for enhancing understanding within the curriculum. Whereas visualizations often focus solely on core scientific concepts targeted by instruction, the tactile model focuses on tangential but critical experientially supported ideas that are disruptive to students' integration of the instructed concepts in conjunction with these instructed concepts. This research therefore builds not only on the literature about the nature and role of student's experientially supported ideas in conceptual change, but also builds on our understanding of visualization and curriculum design to support students learning about thermodynamics, a science topic on which students perform poorly as shown by the NAEP and TIMSS studies (O'Sullivan, Reese, & Mazzeo, 1997; Schmidt, McKnight, & Raizen, 1997).

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Note

[1]For more information about WISE and Probing Your Surroundings, see http://wise.berkeley.edu to create a free account on WISE at http://wise.berkeley.edu and then go either to the heat and temperature project folder in the WISE library or just type: http://wise.berkeley.edu/teacher/projects/library.php

Appendix A

Thermal Equilibrium and Tactile Test Questions

The test questions included in the thermal equilibrium measure and the tactile measure for the analysis of the visualization strategy are included in this appendix. The core tactile measure includes Item 1. The delayed posttest novel tactile questions include Items 6a and 7a. The combined core thermal equilibrium measure includes Items 2c, 2d, 3, 4, and 5. The delayed posttest thermal equilibrium questions include Items 6b and 7b.

1. Can two objects be the same temperature but feel hotter or colder than each other?

   a. (Circle one) YES NO

What is the **main reason** for your answer?

2. A wooden chair and a metal chair have been in Mr. K's class for 12 hours. You look at the thermometer in the classroom, and it says 23°C in the room.

   a. You touch both the metal and wood chairs. How does the wood chair feel? (Check one)

      ____ The wood chair feels warm.
      ____ The wood chair does not really feel cool or warm.
      ____ The wood chair feels cool.

   b. How does the metal chair feel compared with the wood chair? (Check one)

      ____ The metal chair feels warmer than the wood chair.
      ____ The metal chair feels the same as the wood chair.
      ____ The metal chair feels colder than the wood chair.

What do you predict is the temperature of the wood chair and metal chair?

   c. Metal Chair ____ °C
   d. Wood Chair ____ °C

3. Karen was baking cookies for the ECK Club bake sale, and she accidentally left a metal spoon and a wooden spoon in the oven. The oven was on, but it was set at 40°C (slightly warm). The next day she found the spoons and, being curious, she measured their temperatures.

What do you predict the temperature of metal spoon and wood spoon is in Celsius?

   a. Metal Spoon ____ °C
   b. Wood Spoon ____ °C

c. Why did you predict the temperature you predicted for the wood spoon? Why did you predict the temperature you predicted for the metal spoon? (please give reasons for both)

4. You arrive at a ski cabin during the winter and no heat was left on. The room thermometer reads **5°C**. What can you predict about the temperature of a wool sweater, metal shovel, and wood table in the cabin?

   a. Wool sweater ____ °C
   b. Metal shovel ____ °C
   c. Wood table ____ °C
   d. Why did you choose your estimated temperature for each object?

5. Pat and Sasha are running an errand for their parents to buy several long strips of metal and several long strips of wood at a hardware store. They put the strips in the trunk of the car. It is a hot day and they stopped at another friend's house on the way home since they were not in a hurry. When they finally get home, Pat and Sasha have different predictions about the temperature of the strips of metal and wood in the trunk.

   a. Who is right? (Check the answer you think is correct)

   ____ Pat (who thinks the wooden strips would be a higher temperature than the metal strips.)
   ____ Sasha (who says that the metal strips would be a higher temperature than the wooden strips.)
   ____ Neither of them is right.

   b. What is the **main reason** for your answer?

6. Imagine you have a metal bowl that is 0°C and a wood bowl that is 0°C (0°C is the temperature at which water freezes).

   a. Do they feel the same, does the metal one feel colder, or does the wood one feel colder? (Check one)

   ____ They feel the same
   ____ The metal bowl feels colder
   ____ The wood bowl feels colder

What is the **main reason** for your answer?

   b. Imagine that you bring them into a 23°C room. (23°C is a normal room temperature) What temperature will the wood and metal bowls be after 24 hours?

   Temperature of metal bowl after 24 hours = ____ °C
   Temperature of wood bowl after 24 hours = ____ °C

What is the main reason for the temperatures you predicted for the wood and metal bowls?

7. Imagine you have a metal bowl that is 47°C and a wood bowl that is 47°C (47°C is 10°C warmer than your body temperature.)

   a. Do they feel the same, does the metal one feel hotter, or does the wood one feel hotter? (Check one)

   ____ They feel the same
   ____ The metal bowl feels hotter
   ____ The wood bowl feels hotter

What is the **main reason** for your answer?

b. Imagine that you bring them into a 23°C room. (23°C is a normal room temperature) What temperature will the wood and metal bowls be after 24 hours?

Temperature of metal bowl after 24 hours = ____ °C
Temperature of wood bowl after 24 hours = ____ °C

What is the main reason for the temperatures you predicted for the wood and metal bowls?

Appendix B

Interview Questions

The interview questions closely resemble the test questions. The order was not the same, but the goal involved clarification of the test results.

1. Ski cabin
   You arrive at a ski cabin during the winter and no heat was left on. The room thermometer reads 5°C. What can you predict about the temperature of a wool sweater, metal shovel, and wood table in the cabin? (Why did you choose your estimated temperature for each object?)

2. Car trunk
   Pat and Sasha are running an errand for their parents to buy several long strips of metal and several long strips of wood at a hardware store. They put the strips in the trunk of the car. It is a hot day and they stopped at another friend's house on the way home since they were not in a hurry. When they finally get home, Pat thinks the wooden strips would be a higher temperature than the metal strips. Sasha thinks the metal strips would be a higher temperature than the wooden strips. Who is right? Pat, Sasha, or neither of them? (What is the main reason for your answer?)

3. Spoons
   Karen was baking cookies for the Outdoors Club bake sale, and she accidentally left a metal spoon and a wooden spoon in the oven. The oven was on, but it was set at 40°C (slightly warm—about 102°F). The next day she found the spoons and, being curious, she measured their temperatures. What do you predict the temperature of metal spoon and wood spoon is in Celsius? Why did you predict the temperature you predicted for the wood spoon? (Why did you predict the temperature you predicted for the metal spoon? Please give reasons for both.)

4. Wood chair and metal chair
   A wooden chair and a metal chair have been in the classroom for 12 hours. You look at the thermometer in the classroom, and it says 23°C in the room. You touch both the metal and wood chairs. How does the wood chair feel? (How does the metal chair feel compared with the wood chair? What do you predict is the temperature of the wood chair and metal chair?)

5. Concepts
   What is a conductor? Insulator? Equilibrium? Are heat energy and temperature the same or different? Explain your answers.

6. Changing temperatures
   Now say that you have a 100°C cookies that you pulled out of the oven a few minutes ago and you put them in the refrigerator which is 4°C. What happens to the

temperature of the cookies and why does it happen? What happens if we take frozen hamburgers, 0°C, pull them out of the freezer, and we put them in an 80°C oven?. Why?

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