Demonstrating the Temperature-Dependence of Scientific Phenomena for Middle Schoolers

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ABSTRACT

A collection of four activities for science outreach events was developed to teach middle school students about the temperature dependence of scientific phenomena. Procedures are described for four interactive demonstrations on phase changes, fluorescence, viscosity effects on diffusion, and conductivity. Each hands-on activity helps students visualize the scientific concept under investigation while they use the scientific method to evaluate the effects of temperature on experiment outcomes. Activities were designed to be completed relatively quickly and at low cost, which facilitates their incorporation into science outreach events.

KEYWORDS

Demonstrations; middle school; temperature; phase change; fluorescence; viscosity; diffusion; conductivity

INTRODUCTION

Temperature is a simple concept that children learn at an early age. Whether it is hot or cold outside dictates if they should wear shorts to school or bring a jacket. Although the basic notion of temperature is intuitive, its connection to scientific phenomena is often not learned until the undergraduate or graduate levels. However, some scientific demonstrations have been designed to teach students at earlier ages how temperature impacts the behavior of materials. A common example is the effect of liquid nitrogen on objects. Materials immersed in a liquid nitrogen bath cool to -196 °C, which reduces molecular motion and freezes the water inside of biological samples. One popular experiment that demonstrates this effect is freezing a banana and then shattering it with a hammer. [1] This illustrates for students that the water inside the banana freezes into a hard solid, but the ice crystals within are brittle and can be readily broken by applying pressure (i.e. the hammer). Similarly, many demonstrations show that cooling polymeric objects affects their physical properties. For example, the ability of polymer balls to bounce is affected by temperature. [2] Similar to happy/sad ball toys that illustrate elastic versus inelastic collisions, the extent of rebound of a single ball after it hits the floor can be impacted by changing its temperature. [3] Cooling the ball reduces the motion of its polymer chains and converts them from a viscoelastic state to a glassy state. [4] This conversion makes the polymers brittle rather than flexible, [5] which prevents them from rebounding after impact. These examples provide interactive illustrations for students of how temperature impacts objects. However, countless scientific phenomena exhibit temperature dependence. We assert that developing similar demonstrations to illustrate temperature effects on less tangible scientific phenomena—beyond solid objects—will provide a more comprehensive education for students.

This article describes a collection of four activities that highlight how temperature affects phase changes, fluorescence, viscosity effects on diffusion, and conductivity. These simple experiments were developed to teach middle school students, but they can be adapted to different education levels (e.g. high school, college). These activities were originally designed to serve as modules for science outreach events for students in 5^{th}–8^{th} grade, each module taking ~15 min to complete. The interactive engagement of the experiments maintained the attention of students (no one fell asleep!) and provided them with experience in real-world scientific practices including hypothesis generation, conducting experiments, recording observations, and drawing conclusions from the data collected. Although no formal learning assessments were given at our pilot outreach events, the lead instructor queried the students at the end of each experiment to recap learning outcomes. Students enthusiastically raised their hands to explain what they had seen and learned. Student answers for both the experimental results and the fundamental scientific phenomena were universally correct at each of our events. Based on our experiences, coupling a brief lecture overview with a colorful interactive activity was an effective strategy to help students understand complex scientific concepts within the short timeframe of the activities.

METHODS AND MATERIALS

Please see the Supporting Information (SI) for descriptions of reagent preparation, instructions for experimental demonstrations, and discussions of potential hazards. Details needed to successfully carry out the activities (e.g. teaching points, activity organization) are also described in the SI for each experiment.

RESULTS AND DISCUSSION

1. PHASE CHANGES

The Phase Change Experiment developed here provides an interactive example to teach students about phase changes and the impact of temperature. Students were first instructed about phase changes (see SI, Phase Change Experiment). They were then presented with vials containing water, DMSO, or Pluronic thermal gel and asked to form hypotheses about the temperature-dependence of each sample. During outreach events, it is important to stress to students that whether a hypothesis is correct or not is inconsequential, so as not to induce anxiety in the students. Instructors should reiterate that science is about learning and that everyone will find out the correct answer during the experiment. Students then evaluated the samples at room temperature (~23 °C), in an ice bath (~0 °C), and in a hot water bath (~60 °C) and recorded their observations on the Phase Change Experiment Observation Sheet (see SI).

Results from the experiment highlighted the distinct phase change properties of each sample. The water sample remained liquid at each temperature (Figure 1, left). This demonstrates that a 0 °C ice bath is not sufficiently cold to freeze the water in the vial, which explains why household freezers are generally held at -20 °C. Similarly, the hot water bath is insufficient to boil the water in the vial. The bath was below the boiling point of water, thus the water sample could not convert into steam.

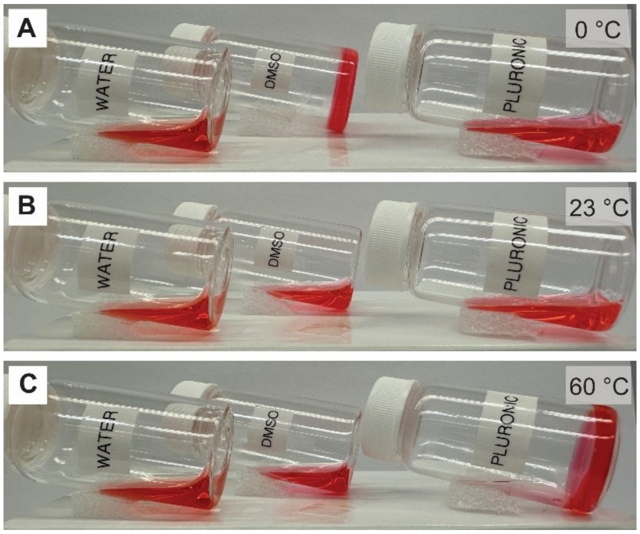

Figure 1. Pictures of water, DMSO, and Pluronic thermal gel after a 1-min incubation **(A)** in an ice bath, **(B)** at room temperature, and **(C)** in a hot water bath. Water remains fluid at all temperatures. DMSO solidifies in the ice bath but is liquid at warmer temperatures. Pluronic thermal gel is liquid at or below room temperature but solidifies when heated.

The DMSO sample remained liquid at room temperature and high temperature, but it solidified in the ice bath (Figure 1, middle). DMSO nicely demonstrates that different solutions have distinct freezing points. Although the water remained liquid at 0 °C, DMSO has a higher freezing point (18 °C),[6] thus it solidified in the ice bath. When heated in the hot water bath, the DMSO melted to reform into a liquid. Although students are familiar with the properties of water, they should note that numerous different solvents are used in scientific research and manufacturing industries, each solvent having its own unique properties.

The Pluronic thermal gel sample remained liquid at room temperature and in the ice bath, but it solidified in the hot water bath (Figure 1, right). Thermal gel highlights that some materials demonstrate counter-intuitive behaviors and defy predictions. Middle school students accept that statement at face value (based on our experiences), but for higher level classes (e.g. college), additional explanations can be provided to explain why this occurs. Thermal gels are made from Pluronic triblock copolymers. Each Pluronic unimer has a hydrophobic polypropylene oxide (PPO) subunit flanked by two hydrophilic polyethylene oxide (PEO) subunits (Figure 2).[7] This triblock structure gives rise to interesting properties in aqueous solutions. At lower temperatures (e.g. <15 °C), water molecules can hydrate the hydrophobic subunits, which results in a mixture of soluble unimers and micelles (Figure 2, blue). The thermal gel exists in a liquid phase at these low temperatures. When the temperature is increased (e.g. >30 °C), PPO subunits become dehydrated, causing unimers to aggregate into micelles having hydrophobic PPO cores and hydrophilic PEO corona that extend into solution (Figure 2, red). Once a critical number of micelles form, they close-pack into an ordered crystalline lattice, which converts the thermal gel into a solid phase. Although the phase change properties of thermal gel are uncommon, this unexpected outcome excited students because it did not conform to their preconceived notions. This teaches students that there can be exceptions to general rules and to keep an open mind in their thinking. Collectively, this activity provides students with a colorful hands-on demonstration to illustrate phase transitions, freezing points, and polymer micellization and teaches how temperature is critical to these phenomena.

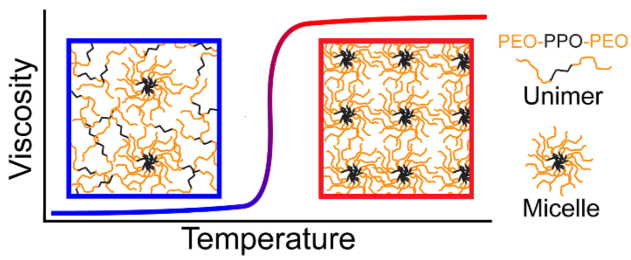

Figure 2. Pluronic copolymers form micelles whose stabilities are governed by temperature. Colder temperatures destabilize micelles, which results in a mixture of solution-phase unimers and micelles (left). Warmer temperatures cause unimers to aggregate into micelles, which then assemble into a high-viscosity, solid-phase lattice (right). Figure adapted from Reference 6. PEO: polyethylene oxide; PPO: polypropylene oxide.

2. FLUORESCENCE

The Fluorescence Experiment described here helps students visualize fluorescence and evaluate its response to temperature-induced molecular motion. Students were first instructed about fluorescence and absorbance (see SI, Fluorescence Experiment) and then asked to create a hypothesis for how the molecular motion at different temperatures would impact the observed fluorescence. Three vials containing the same fluorescein solution were then presented to the students to evaluate at room temperature (~23 °C), in an ice bath (~0 °C), and in a hot water bath (~60 °C). Students qualitatively evaluated both the color of the sample and the intensity of the glow (e.g. low, medium, high) upon irradiation with a blue flashlight and recorded their findings on the Fluorescence Experiment Observation Sheet (see SI).

Results from these experiments revealed that all solutions had a similar yellow/orange color regardless of temperature (Figure 3A). This indicates that fluorescein absorbs ambient light similarly at all temperatures. Dye emission, however, was highly dependent on temperature. At lower temperatures (i.e. ice bath, room temperature), clear fluorescence was observed from the fluorescein (Figures 3B and 3C). This indicates that radiative relaxation of the excited state fluorophore was favorable because of the lower molecular motion at cooler temperatures. The photons emitted from these samples caused the solution to glow. At higher temperatures (i.e. hot water bath), molecular motion in the sample is higher, which causes the excited state fluorescein molecules to undergo more collisions with other molecules. This motion decreases the quantum yield of the dye and favors non-radiative relaxation to the ground state, as indicated by reduced fluorescence emission (Figure 3D). Collectively, these simple experiments using fun glowing reagents enable students to clearly visualize how temperature-induced molecular motion influences emission of the fluorescent dye. It demonstrates that absorbance has only a minor temperature dependence, but that fluorescence emission is sensitive to temperature.

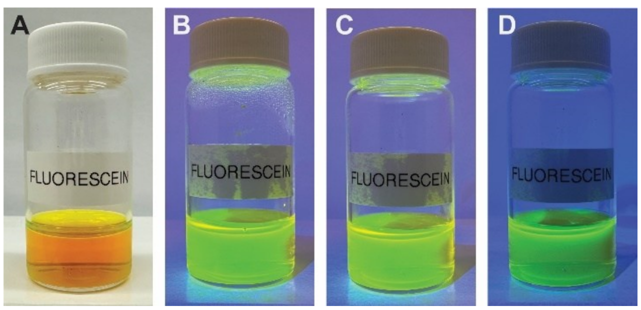

Figure 3. (A) Picture of a 1 mM fluorescein sample under ambient lighting. **(B–D)** Pictures of the fluorescein sample under blue light when the sample was incubated **(B)** in an ice bath, **(C)** at room temperature, and **(D)** in a hot water bath. Fluorescence is observed as opaque haziness in the cold and room temperature solutions. However, when heated, the sample appears noticeably more transparent because emission is significantly quenched. Note that fluorescence is difficult to clearly capture on camera; differences between temperatures are more pronounced in person.

3. VISCOSITY EFFECTS ON DIFFUSION

The Viscosity-Diffusion Experiment discussed here illustrates diffusion for students and shows how temperature-dependent solution viscosity impacts the rates. Students were first instructed on the concepts of diffusion and viscosity (see SI, Diffusion-Viscosity Experiment). Vials of room temperature water and glycerol were placed in front of the students. Students were prompted to evaluate the vials to determine the relative viscosities of the solutions and then form a hypothesis about the expected rates of diffusion in each. The experiment was then conducted where food coloring was added to vials of each liquid equilibrated at room temperature (~23 °C), in an ice bath (~0 °C), and in a hot water bath (~60 °C). Students carefully observed each solution and recorded the qualitative rates of diffusion (e.g. slow, medium, fast) on the Viscosity-Diffusion Experiment Observation Sheet (see SI).

Results from the experiment revealed that food coloring added to room-temperature water exhibited noticeable diffusion as the concentrated color drop dispersed into solution within ~10 s (Figure 4A, middle), although longer times were required to obtain a homogenous mixture. The room-temperature glycerol sample, however, exhibited only minor diffusion, as the food coloring diffused into solution very slowly. The solution remained obviously heterogenous even 1 min later (Figure 4B, middle). Food coloring added to the hot water exhibited high rates of diffusive mixing, as the color rapidly dispersed through the sample (Figure 4A, right). Diffusion was slower in the high-temperature glycerol (Figure 4B, right); however, the food coloring drop dispersed over a significantly larger volume than the room temperature glycerol sample. Food coloring slowly diffused through the cold water (Figure 4A, left) but did not diffuse through the cold glycerol (Figure 4B, left). The drop remained mainly intact on the glycerol surface. These results demonstrate the temperature-dependence of diffusion and the influence of solution viscosity. Diffusion observed through water was universally higher than diffusion through glycerol, which stems from the 1000-fold higher viscosity of glycerol (at 25 °C).[6] Solutions with higher viscosity restrict molecules from moving through, as illustrated by the lower rates of diffusion. Viscosity is inversely related to temperature. Thus, higher temperatures reduce solution viscosity, which in turn increases diffusion rates, as observed in both water and glycerol samples. This simple experiment provides a colorful demonstration of diffusion and viscosity to middle school students while accentuating temperature effects.

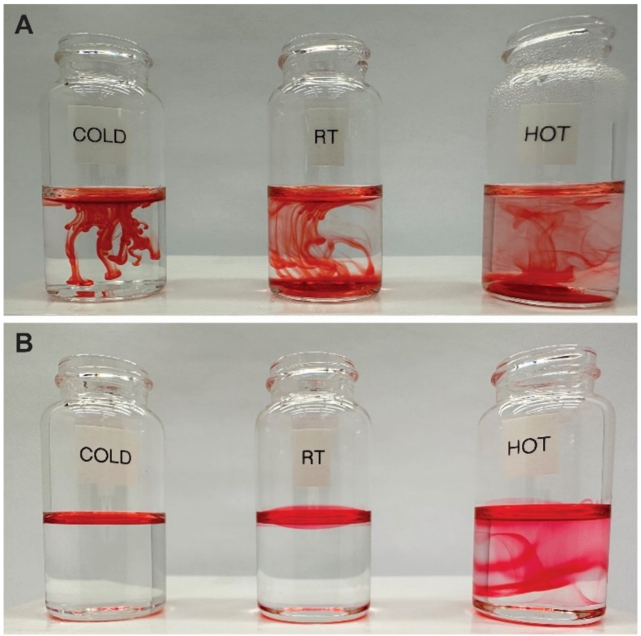

Figure 4. The diffusion of food coloring was monitored in **(A)** water after 10 s and **(B)** glycerol after 1 min. Diffusion is more prominent in lower viscosity water than higher viscosity glycerol across all temperatures. Within a given solution, diffusion increases as temperature is increased from an ice bath (cold) to room temperature (RT) to a hot water bath (hot) because of higher thermal motion.

4. CONDUCTIVITY

The Conductivity Experiment developed here illustrates solution conductivity while reinforcing the effect of temperature on ion motion. Students were first instructed about conductivity (see SI, Conductivity Experiment) and then asked to form a hypothesis on how to distinguish tap water from “salt water” based on conductivity measurements and also predict the effects of temperature on the measurement. Students were then presented with cups of each sample and asked to evaluate them at room temperature (~23 °C), in an ice bath (~0 °C), and in a hot water bath (~60 °C). An at-home conductivity meter was used to analyze samples by immersing the probe in solution (Figure 5). The quantitative reading displayed was then recorded on the Conductivity Experiment Observation Sheet (see SI).

Figure 5. Samples were analyzed by immersing a conductivity meter probe into solution. Conductivity values (in units of μS/cm) of salt water were larger than tap water because of the higher ion content. Higher temperatures increased conductivity for both samples because of the enhanced thermal motion.

Results from this experiment revealed that one sample had significantly higher conductivity than the other (Table S1). Unanimously, students correctly identified the "salt water" because its higher electrolyte content made it more conductive. Temperature effects were then assessed. Conductivity values were significantly higher in the heated samples, which stems from their higher thermal energy. Ion motion increased leading to higher solution conductivity. To validate this trend, low-temperature samples were analyzed, where lower conductivities were observed. Ion motion was suppressed when thermal energy was low, which reduced the measured conductivity. Outcomes from this experiment demonstrate that ion concentrations impact conductivity and that the increased thermal motion at high temperatures increases the measured conductivities as well.

CONCLUSIONS

This article describes four activities that provide students with hands-on opportunities to learn about real-world scientific phenomena. Using interactive experiments to illustrate the phenomena helps students visualize important scientific principles while also showing them how temperature plays a significant role in their behaviors. Each experiment was designed to be hands-on to engage students and keep their attention, which is critical in science outreach events. Experiments were also designed to quickly produce results—with minimal time spent idle—to prevent students from losing focus. The brief dwell times in experiments were filled with discussions where students made hypotheses or interpreted data, which provided them with valuable experience using the scientific method. Although the quality of hypotheses and interpretations varied between groups, all students gained extracurricular experience with these important scientific practices. Finally, experiments were designed to be operated at low cost. Minimal reagents are required to run the demonstrations and the equipment needed is inexpensive. The low cost and ease of experimental preparation make these activity modules accessible for most outreach events.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Overview of pilot outreach events; Instructor's guide on reagent preparation, teaching points, and experiment instructions; Student observation sheets for each activity

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