PAPER

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Teaching thermal physics to Year 9 students: the thinking frames approach

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Abstract

Students hold many alternative conceptions of thermal physics which are very resistant to change. A conceptual change strategy, the thinking frames approach, based on evidence from educational research was used to address commonly held naïve conceptions about heat in a series of thermal physics lessons. Students' gains in conceptual understanding were measured in two Year 9 classes using pre/post-tests. These results were compared to conceptual gains of a class learning the same topics by more traditional means. Results showed that learning thermal physics with the thinking frames approach led to a much greater increase in understanding (Effect size = 2.04) compared to learning with traditional methods (Effect size = 0.20).

1. Introduction

Students experience heat in many contexts in their daily lives and develop conceptual frameworks in order to explain and understand these phenomena which involve many alternative beliefs that are very resistant to change [1]. Some of the most widespread beliefs are that heat and cold are substances which flow from one place to another, that heat rises, that metals are intrinsically colder than other materials, that temperature is a measure of heat and that temperature always increases when a substance is heated [2].

Belief that heat is a substance in its own right often underpins students' understanding of thermal energy transfers rather than basing understanding on a process-based model involving transfer of kinetic energy to or from particles and an understanding of the intrinsic properties of those particles such as specific heat capacity or atomic structure [3]. Students often complete courses in thermal physics without undergoing statistically significant conceptual change [4, 5] and even some adults who may be considered experts had difficulty applying the thermodynamic concepts in everyday situations [2, 6]. One difficulty appears to be that students find visualising concepts such as thermal energy transfer between objects to explain observations such as metals feeling cold to touch challenging. Use of thermal imaging to challenge students' alternative conceptions about thermal energy transfer and to provide real-time visual observations of these processes has been a fruitful way forward in helping students adopt scientific understanding [7].

In order to address alternative conceptions, the first author identified six commonly held conceptions and designed lessons to challenge these conceptions and help students build scientific explanations of their observations. These lessons were based on the thinking frames approach (TFA), originally developed by teaching colleagues and academics in England [8] to develop deeper scientific thinking in senior primary school students. The approach combines observation of a demonstration to challenge students' alternative conceptions with construction of verbal explanations in small groups through a predict-discuss-explain, observe-discuss-explain cycle. The teacher guides this construction through careful questioning. In order to encourage greater visualisation of the processes occurring, students then transfer their explanations into both pictorial and written forms and finally evaluate their explanations in terms of how persuasively they have linked scientific understanding to their observations. To illustrate the approach, one lesson challenging students' belief that metals are intrinsically cold is described. While this alternative conception is well-known and researched, it has proven to be resilient to teaching. With this group of Year 9 students, the use of the TFA had dramatic learning outcomes.

2. Theoretical framework

There has been much research on how to support students as they undergo conceptual change and transition from their naïve alternative conceptions of the world towards adopting scientific explanations for those phenomena [9]. In particular studies have shown the power of making students' alternative conceptions visible to both themselves and their peers and challenging those conceptions with demonstrations [9]. More recently, the importance of giving students opportunities to undergo multidimensional conceptual change by addressing cognitive aspects of that change within a social context, through small group and whole class dialogue, and consideration of affective aspects of learning, such as motivation, self-efficacy and emotions, has been a focus of conceptual change research [9]. Students' representations of their conceptual understanding in different modes such as verbal, pictorial and written, has been shown to provide further support for development of scientific conceptual understanding [10]. The TFA is a multidimensional conceptual change approach that utilises each of these strategies suggested in the literature.

3. TFA lessons

The teacher began the lesson by posing a question for students to discuss in their small groups—'Which will melt first—a block of ice placed on a metal plate or one placed on a ceramic plate?' After discussion, students from each group presented their ideas to the class with justifications. This allowed students' concepts and the underlying model of heat transfer that they held to be visible to the teacher and the rest of the class and to be contrasted with their later observations.

Karen: We thought the ceramic one would melt faster because the metal would absorb the cold energy and then make the metal [cold] and then the ice would stay cold.

Karen's response indicated that she had not understood the process-based nature of kinetic energy transfer and that she still thought that there was a 'cold energy' entity. Students almost exclusively predicted that the ice on the ceramic plate would melt first because metals are colder than ceramic. The experiment was then carried out and students observed that the ice on the metal plate melted much faster. Students returned to their small groups to discuss and explain their observations. They then presented their new explanations to the class and the teacher encouraged greater elaboration of ideas through questioning as she attempted to turn students' attention to the ideas of energy transfer and the intrinsic properties of metals and ceramics which allow for more rapid transfer of energy until thermal equilibrium is reached. The following class discussion occurred as students presented their explanations to the teacher (T) why the ice cube on the metal plate melted much faster. (Numbering is used to identify turns in the dialogue. Only relevant parts of the dialogue are included and sections which involved side-discussions have been removed):

1. Kyle: Maybe it's because the metals bring the cold from other things better, since they try to transfer the thermal energy around. So they are basically good heat conductors they hold that little piece of heat and try to spread it out and so it also making the metal colder. […]

2. T: What temperature did the [ceramic] plate and the metal start off at?
3. Sam: Room temperature. […]
5. Kate: Um I touched the metal and I touched the ceramic plate but the ceramic plate was warmer.
6 T: OK. Why does the metal feel colder than the ceramic plate?
7. Karen: Because it absorbs the cold energy of the ice.
8. T: Is there such a thing as 'cold' energy?
9. Malcolm: Is it because it's not as good a conductor so it will not conduct as well into the hand?
10. David: When you touch the metal, the metal takes the heat away from you and absorbs it better.
11. T: That's right! What temperature is your hand at?
12. Karen: 97 degrees? [Various other suggestions]
13. T: 37 degrees. And room temperature is around 20 degrees today. […] So there are some things that are colder in this room than others. Is that true?
20. David: No […]
23. T: No? Why do they feel different then?
24. Rachel: Because some things are better conductors than others.
26. Jacob: I think there are colder things because there are ice cubes.
[Students ask about whether it is possible for something to have no thermal energy]
38. Catriona: If you had two metal containers and you had an ice cube on both and you put your finger or your hand on one of them, would that one melt faster?
39. T: What do you think?
40. Catriona: Yeah
41. T: Why?
42. Catriona: Because your hand has more thermal energy in it [is a higher temperature] and it [the metal] is conducting it around

Students were asked to think about their observations and explanations based on concepts learned in prior lessons, such as transfer of energy from bodies at higher temperature to those at lower temperature and different conductivity of materials based on their structure. The teacher tried to ensure that students had the opportunity to construct their own understanding at this point rather than giving an explanation. It can be seen that students recognised that there was something incorrect about their initial explanations due to their observations of the ice melting faster on the metal plate (line 1). However, they then thought that the metal was a good conductor of 'cold' rather than recognising that materials may only possess less or more thermal energy (lines 1–7). The discussion was able to lead students to focus on energy transfer between objects of higher to those of lower temperature (lines 2–3, 11–20), the importance of the intrinsic conductivity of materials to determine the rate of that transfer and thus to address the belief that metals are colder than ceramics (lines 5–24). This led to Catriona synthesising these two concepts to suggest that putting your finger on the metal plate would speed up the process of melting even further (lines 38–42). Once students had developed verbal explanations of their observations and concepts they had learned in previous TFA lessons about the way heat is transferred in metals, they chose keywords that they believed were essential to answer the question scientifically, such as thermal equilibrium, covalent bonding, metallic bonding, conducting, thermal energy, transfer of heat. They then drew explanatory pictures of the two scenarios. Students were encouraged to make their drawings explanatory and they did not have to use conventional symbols but were allowed to invent their own methods to communicate their understanding. Some drawings focused on the temperature differences and used arrows of different sizes to show the direction of transfer of thermal energy from the room to the metallic plate to the ice cube and compared this with the ceramic plate, where thermal energy mainly transferred from the area of the plate directly in contact with the ice. Others focused on the rate of energy transfer, comparing the structure of the metal versus the ceramic. Following this, students organised their ideas into written dot points, and wrote an extended paragraph explaining their observations and answering the question. Finally, they evaluated their written explanations against a rubric based on the Levels Mountain [11] which encourages linking of observations to the underlying model of matter, elaboration of ideas and use of scientific vocabulary. Levels 1 and 2 of the rubric indicate a description of what happened,

Table 1. Thermal physics TFA lessons.

Lesson topics	Guiding questions
Thermal equilibrium	Explain how the temperature changes when 'hot' (77 °C) water is mixed with 'cold' (19 °C) water
Conduction	Explain why the drawing pins fell off the metal rods sooner than the glass rod when heated on the other ends
Melting ice	Explain why ice on the metal plate melted faster than on the ceramic plate
Convection	Explain how a whole room can heat up if a radiator is in the corner. How does double glazing help to keep the room warm?
Latent heat	Explain why the temperature of water increases as we heat it from 0 °C to 100 °C but then stays at 100 °C
Heating a paper cup	Explain why a paper cup with water in it does not burn when placed over a Bunsen burner

Item 1: What is the most likely temperature of ice cubes stored in a refrigerator's freezer compartment?

a. -10^{o}C
b. 0^{o}C
c. 5^{o}C
d. It depends on the size of the ice cubes

Item 16: Kim takes a metal ruler and a wooden ruler from his pencil case. He announces that the metal one feels colder than the wooden one. What is your preferred explanation?

a. Metal conducts energy away from his hand more rapidly than wood
b. Wood is a naturally warmer substance than metal
c. The wooden ruler contains more heat than the metal ruler
d. Metals are better heat radiators than wood
e. Cold flows more readily from a metal

Figure 1. Examples of items from the TCE [12].

while level 3 indicates that students have provided a simple explanation of their observations. Level 4 requires a more detailed explanation and use of scientific vocabulary, while Level 5 is an elaborated and persuasive causal explanation based on underlying scientific models.

4. Research design

This study involved two Year 9 groups, $9E_{\mathrm{A}}$ and $9E_{\mathrm{B}}$ in consecutive years. Each class was taught by the first author using the TFA. In the second year a comparison class, $9C_{\mathrm{B}}$, taught by an experienced teacher, was also taught the same topics using the same demonstrations but otherwise the teacher continued with the usual teaching practices of showing videos, class discussions and answering text-book questions. Students completed 12 lessons over three weeks in the topic of thermal physics. Of these 12 lessons, the experimental groups completed the six TFA questions described in table 1, each question being answered during one 50 min class period. Class $9E_{\mathrm{B}}$ completed an extra TFA lesson about heat capacity.

Students were given a thermal physics conceptual test developed for use with senior high school and university students, the Thermal Concept Evaluation (figure 1) [12], before learning about thermal physics and directly after teaching. Students from $9E_{\mathrm{A}}$ were also given this test six months after completing the thermal physics topic to determine whether or not their conceptual gains had been retained.

This study sought to answer the question: Does teaching with the TFA result in greater conceptual understanding of thermal physics compared to more traditional methods and does this change persist?

5. Results

$9E_{\mathrm{A}}$ students' pre/post and delayed post-test scores on the TCE are presented in figure 2. After the teaching period using the TFA, all but three students had improved scores on the TCE. A total

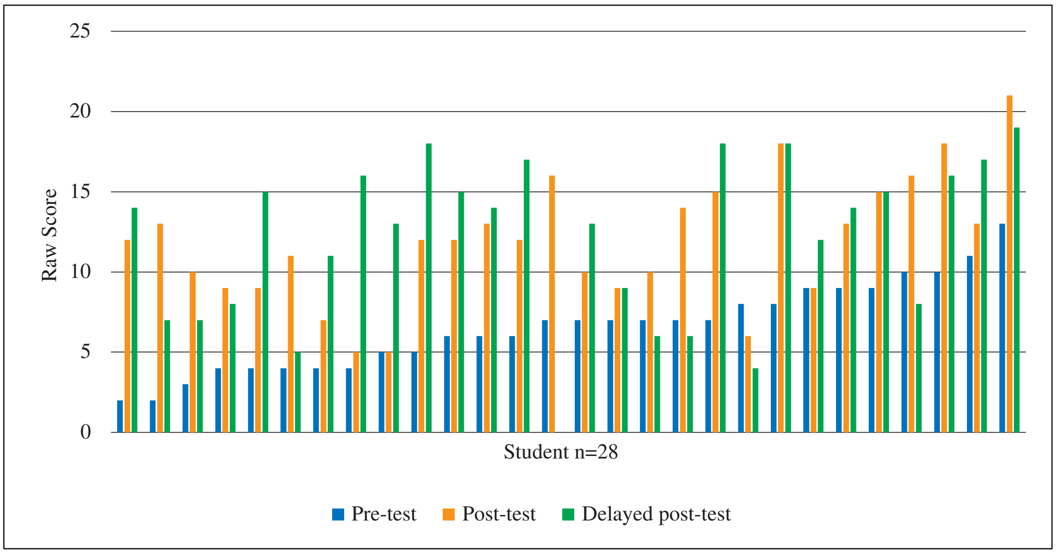

Figure 2. Class $9E_A$ individual students' raw pre/post and delayed post TCE scores (max. 26) presented in order of pre-test results. $M_{pre} = 25\%$, SD = 11%, $M_{post} = 46\%$, SD = 15% $M_{delayed} = 48\%$, SD = 18%, $t = 8.5$, $p < 0.0001$.

of 18 students had equivalent or higher delayed post-test scores than scores obtained straight after the teaching period even though no further teaching of thermal physics concepts had occurred. Surprisingly, two of the three students who had not shown conceptual gains between the pre and post-tests displayed gains in the delayed post-test after six months. Students had not been shown the correct answers on the TCE after administration of any of the tests, although they had been told their scores. The delayed post-test scores indicate that students had retained and, even in some cases, developed greater scientific conceptual understanding of thermal physics over this period. The six students with lower delayed post-test scores than post-test scores, still had higher scores than their pre-test scores indicating that some of the conceptual gains had been retained over the six-month period. The Cohen effect size for learning thermal physics with the TFA, which is calculated by finding the difference between pre- and post-test TCE means divided by the pooled standard deviation was 1.57. A Cohen effect size indicates how large the effect is as a result of a particular intervention, and a value of greater than 0.80 is generally considered to be a large effect. For instance, Hattie [13] found that the average effect size for interventions in education was 0.40.

Likewise, in the second year of the intervention students of the experimental class, $9E_B$, showed significant conceptual gains, while students of the comparison class, $9C_B$, on average underwent no significant conceptual change (figure 3). The Cohen's effect size, comparing pre and post-test means for the experimental group, $9E_B$, of 2.04, was higher than for the previous cohort which could have been related to the teacher's growing familiarity with the TFA process, particularly the questioning strategies required and the extra lesson on heat capacity.

The TCE is a conceptual test which does not require use of mathematical formulas. However, it was designed for use with senior high school or university students studying physics, and research using this test has been extensively reported. It was expected that a mixed ability class of Year 9 students studying general science would find this test challenging. In order to better understand how well the conceptual gains of the Year 9 experimental groups compared to other students learning thermal physics they were compared with results from Yeo and Zadnik's [12] study which used the TCE to compare understanding of thermal physics amongst students studying general science in Year 10, physics students from Years 11 and 12 and first year university physics students (Year 13) in nine different Western Australian institutions. The Year 11 and 12 students and the university students had recently completed studies in thermal physics topics. Year 10 had studied

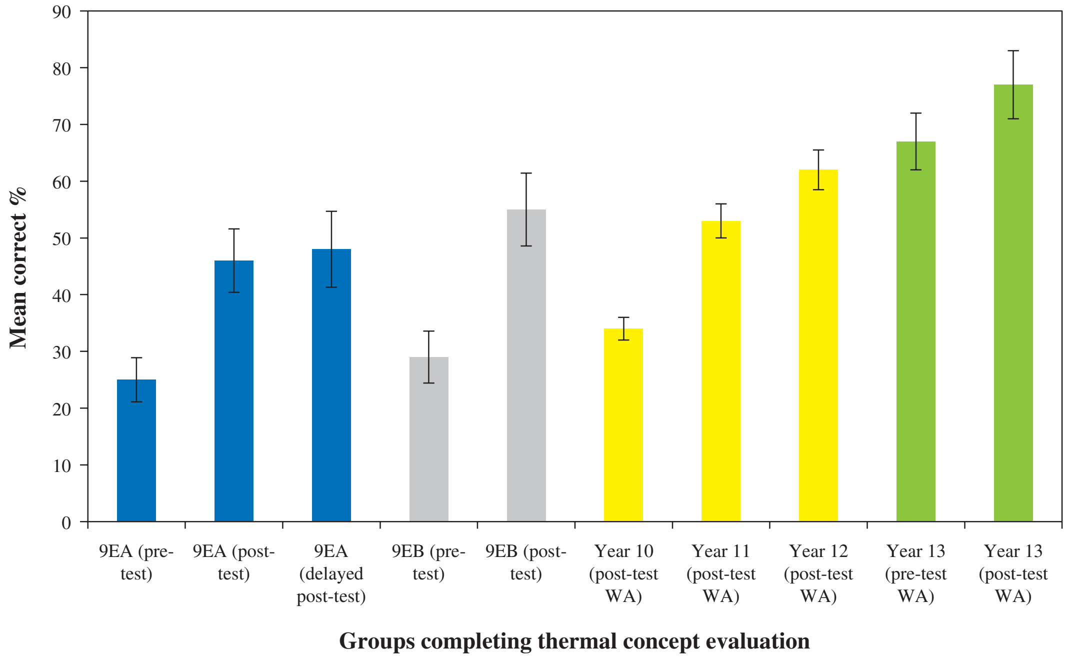

Figure 3. Comparison of mean TCE scores by group with 95% confidence intervals. Results for $9E_B$: $M_{pre} = 29\%$, $SD_{pre} = 11\%$, $M_{post} = 55\%$, $SD_{post} = 15\%$, $t = 11$, $p < 0.0001$; and $9C_B$: $M_{pre} = 33\%$, $SD_{pre} = 10\%$, $M_{post} = 30\%$, $SD_{post} = 11\%$, $t = -1.1$, $p = 0.38$.

thermal physics concepts within their general science course. A comparison between these results and the results of this study can be seen in figure 3 which shows that Class $9E_A$ had, on average, replaced more of the alternate understandings in thermal physics with appropriate explanations than the WA Year 10 cohort but less than the older cohorts while Class $9E_B$ had a mean score commensurate with WA Year 11 Physics students.

6. Discussion

The evidence collected from pre/post-tests from the two classes that learned with the TFA compared to the results from the comparison class suggest that the TFA is a powerful teaching method for supporting students' long-lasting conceptual change in understanding thermal physics. A number of factors worked together to encourage deeper engagement with the scientific model and the teaching approach supported students in constructing their own explanations of phenomena. Firstly, the predict-discuss-explain, observe-discuss-explain format involving a demonstration which challenges students' alternative conceptions, captured student attention and allowed all students to be involved in the process of explanation construction [9]. Secondly, dialogic teacher-student interactions as students' presented their explanations allowed the teacher to guide the students as they constructed verbal explanations and drew attention to the scientific model without direct teaching of concepts. Thirdly, working in small groups to craft verbal, pictorial and written explanations, gave students the opportunity to put forward their ideas in a less threatening environment than the larger class, seeking and receiving feedback from peers as they co-construct arguments. Fourthly, as each student was involved in producing explanations in verbal, pictorial and written modes, the affordances of each mode forced them to consider the explanation from different perspectives and each subsequent explanation encourages further elaboration of the prior mode of explanation [10]. Finally, self-evaluation of the written product encouraged greater self-regulation to ensure efficacy in communication of their understanding.

In interviews with students they noted the importance of each of these aspects of the TFA which made it effective for building understanding of thermal physics. Warren summed up his experience learning with the TFA as follows:

Every time we get a TFA [lesson] we know that it will be a stressful, hardworking lesson and that's really tiring. But it is definitely the most that we will learn because our brains do not stop and we have to write a whole lot. Usually in other lessons we get small breaks in our heads where we will not be using as many thought processes. It is a good thing to push us—it is definitely good. I was more worried than interested [in science]. I felt that I was 2 or 3 years behind and would never catch up but I feel like now I am on the same pace as everyone else. So, it's made it a lot easier and interesting.

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Dr Felicity McLure has taught middle and senior school science for 15 years in international and Australian schools. She introduced the thinking frames approach into her Grade 8-10 classrooms to address problems that she observed with students' building and communication scientific conceptual understanding. She completed her doctoral studies in 2018 and continues to research ways in which student conceptual understanding can be deepened.

Mihye Won is Associate Professor in the School of Education at Curtin University. Her research focuses on various ways to support students' conceptual understanding and scientific thinking skills such as creative and critical thinking. She is currently exploring the use of student-generated multiple representations and new visualisation media such as immersive virtual reality (VR).

Professor David Treagust supervises research students at Curtin University on topics related to understanding students' ideas about science concepts and how these ideas relate to conceptual change and multiple representations, the design of science curricula and teachers' classroom practices.