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To what extent does the use of metacognitive strategies support Year 12 physics students' learning of thermal physics?

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Abstract

Thermal physics is well-known for presenting conceptual challenges that prove highly resistant to traditional teaching and learning. These challenges often stem from students only developing a surface-level understanding of phenomena, without forming deeper generalisations between concepts. This investigation explores whether the use of metacognitive strategies in lessons (specifically, concept mapping and prompted planning and evaluation of problem solving) may promote Year 12 students to consciously examine their own understanding of concepts and, in turn, develop more coherent and valid knowledge schemata. Results show that, during a five-lesson intervention, students displayed subtle signs of increased use of metacognitive skills, particularly those relating to planning and to linking concepts with prior knowledge. This paper argues that such strategies therefore warrant consideration for inclusion in teachers' classroom practice, but that significant further work would be needed to prove a causal link to improved student understanding.

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Introduction

That students encounter conceptual challenges when learning physics is clear (Knight, 2004; McDermott, 2001). This is especially true for the topic of thermal physics: whilst it underpins some of the most pervasive everyday phenomena – heat and temperature – its concepts are frequently misunderstood by children and adults alike, even after completing formal science education (Clough & Driver, 1985; Lewis & Linn, 2003). It is with this in mind that this study asks how we can empower students to learn more effectively so as to overcome those conceptual challenges. As described in the literature review, research on metacognition appears to offer strong claims about the potential for the teaching of skills and strategies that can improve pupils' academic outcomes (Perry, Lundie & Golder, 2019), particularly related to students' learning of scientific concepts (Yuruk, Beeth & Andersen, 2009). This report explores whether such benefits extend to the concepts of thermal physics.

In this paper, I summarise an action-research study held with a Year 12 physics class at a UK secondary school. The paper begins by summarising the insights from research on learning thermal physics, before exploring metacognition and investigating how its associated skills and strategies have been linked to effective learning. These findings are then crystalised into the three research questions guiding this study, informing the research design as described in the 'Methodology and Methods' section, and yielding findings that are discussed in 'Analysis and discussion'. Finally, in 'Conclusion and implications', I outline the study's deductions, describing potential messages for informing teaching practice and research, in particular suggesting that students' learning can be supported by encouraging them to reflect on their developing understanding via techniques such as concept mapping.

Literature review

This review begins by considering the challenges students face when learning thermal physics. I then turn to 'metacognition', asking what promise it might hold for enhancing learning. Finally, I review the variety of documented methods for fostering metacognition, alongside the inherent challenges of researching it.

What challenges do students face learning thermal physics?

Alternative conception	Sources
Conceptions of heat	
Heat is a substance or a fluid	(a), (b)
Heat is not energy	(a)
Heat and cold are different, rather than opposite ends of a continuum	(a), (b)
Heat and temperature are the same thing	(a)
Heat is proportional to temperature (only)	(a), (c)
Heat is not measurable or quantifiable	(a)
Conceptions of temperature	
Temperature is the "intensity" of heat	(a)
Skin or touch can determine temperature	(a)
Perceptions of hot and cold are unrelated to energy transfer	(a)
When temperature at boiling remains constant, something is "wrong"	(a)
Boiling point is the maximum temperature a substance can reach	(a)
A cold body contains no heat	(a)
The temperature of an object depends on its size	(a), (b)
Temperature is a property of the material (e.g., metal is naturally colder than plastic)	(b)
There is no limit on the lowest temperature	(a)
Conceptions of heating	
Heating always results in an increase in temperature	(a)
Heat only travels upward / rises	(a)
Temperature can be transferred	(a)
Objects of different temperatures that are in contact with each other do not necessarily move toward the same temperature.	(a)
Hot objects naturally cool down, cold objects naturally warm up	(a)
Heat flows more slowly through conductors making them feel hot	(a)
The kinetic theory does not really explain heat transfer	(a), (b)
Conceptions about "thermal properties" of materials	
Water cannot be at 0°C.	(a)
Materials like wool have the ability to warm things up.	(a)
Some materials are difficult to heat: they are more resistant to heating.	(a)

Table 1: Examples of students' common alternative conceptions within thermal physics

Abridged from Yeo & Zadnik (2001) with selected additions from other sources. Sources denoted by:
(a) Yeo & Zadnik (2001), (b) Clough & Driver (1985), (c) Wattanakasiwich, Taleab, Sharma, & Johnston (2013).

Physics education research offers extensive analysis of the challenges posed by the topics of thermal physics (Clough & Driver, 1985; Harrison, Grayson & Treagust, 1999; Yeo & Zadnik, 2001). These difficulties are typically conceptual, with students' misconceptions found to follow consistent trends (as presented in Table 1) and to be resistant to change, with similar ideas often held by both young children and teenagers (Clough & Driver, 1985), and even by students (and graduates) of university physics courses (Knight, 2004; Lewis & Linn, 2003).

Various explanations exist for these challenges' persistence and prevalence. Following interviews with 84 teenagers across three UK secondary comprehensive schools, Clough and Driver (1985) suggest that it is the pervasiveness of 'hot' and 'cold' phenomena in children's earliest years that leads to deeply-held (and often tacit) conceptualisations that are not displaced via science teaching, with students instead just being "quick at learning verbal labels and scientific-sounding phrases" (p.181) to acquire the surface-level knowledge necessary to satisfy the teacher. Despite their UK origin, these conclusions appear to align with those from other settings. For example, Lewis and Linn's 1994 Californian study (reprinted 2003) found similar misconceptions when interviewing three highly-contrasting groups: (i) 150 students aged 12-14, (ii) nine adult non-scientists, and (iii) eight 'experts' (university staff with Physics or Chemistry PhDs or Masters' degrees). The authors assert that students build these intuitive, but incorrect, conceptions about heat and temperature from everyday observations before reinforcing them through imprecise language use in day-to-day life. They suggest that these conceptions are rarely underpinned by deeper generalisations, reporting that "students regard the statements themselves as sufficient explanation… that require nothing further" (p.S167).

The surface-level nature of these conceptions is further supported by Yeo and Zadnik (2001) in their summary of research into students' thermal physics understandings:

> "(1) Many conceptions are context-dependent and explanations are related to single or isolated situations. Appropriate generalizations are often not recognized.
>
> (2) Students are inconsistent in their explanations; they use different conceptions to explain similar phenomena and generally do not recognize contradictions.
>
> (3) Students do not apply ideas learned in school to 'everyday' situations; they are more likely to express alternative conceptions when explaining real-life situations.
>
> (4) Students' knowledge frameworks often allow them to accept a statement of what is as a sufficient explanation of why. For example, students believe that heat rises, but many accept this as a definitive explanation for convection currents.
>
> (5) Even when students make correct statements, they often admit to being unclear about their ideas."
>
> (Yeo & Zadnik, 2001, p.497)

In summary, the research considered here appears to suggest that students' learning of thermal physics is hampered by the prevalence of resistant alternative conceptions that reflect the lack of a coherent and interconnected conceptual knowledge schema. This hypothesis allows me to define the central problem to be targeted in this research project: how to support students in their learning of thermal physics concepts to overcome Yeo and Zadnik's five challenges above. Specifically, I seek to explore how to support students in their ability to build, iterate and refine their framework of conceptual thermal physics knowledge in order to recognise conceptual generalisations, develop consistent explanations, apply knowledge to unseen and everyday scenarios, and deliver explanations confidently.

Metacognition: central for effective learning?

Given this identified problem, one key factor for learning thermal physics concepts is suggested by Harrison et al. (1999) as "the student consciously examining his or her understandings and knowledge structures" (p.59). This emphasis on awareness of (and reflection on) learning relates to the broader field of metacognition – to which I now turn.

What is meant by metacognition and metacognitive strategies?

Metacognition, commonly summarised as "thinking about thinking" (Perry et al., 2019, p.485), and related ideas around control – or self-regulation – of learning, form some of the most prominent constructs in education. These notions are subject to extensive research (Dignath & Büttner, 2008; Perry et al., 2019; Schraw, Crippen & Hartley, 2006) as well as appearing in mainstream professional guidance, including a recent publication from the Education Endowment Foundation (EEF, 2019). Stemming from ideas introduced by Flavell (1979), metacognition concepts typically concern students' "knowledge and cognition about cognitive phenomena… [and their] monitoring of their own memory, comprehension, and other cognitive enterprises" (p.906).

The field's theoretical framing, however, is contested. Numerous authors acknowledge that the terms metacognition, and relatedly self-regulation, describe "fuzzy" concepts (Akturk & Sahin, 2011, p.3731), with various researchers defining and relating these components differently (Zohar & Barzilai, 2013). For example, Schraw et al. (2006) conceptualise self-regulated learning (which they intermittently exchange for 'self-regulation') as an umbrella term with three sub-components: cognition (information processing skills), meta-cognition (understanding of cognitive processes) and motivation (beliefs and attitudes relating to cognition and metacognition). In contrast, some studies identify metacognition as the umbrella term under which self-regulation sits (Wagaba, Treagust, Chandrasegaran & Won, 2016). This multiplicity of stances makes for a complex theoretical landscape, the clarification of which would be neither feasible nor totally necessary for this study, which is primarily interested in practical methods for supporting thermal physics learning. Instead, I will simply clarify the theoretical perspectives that I will adopt for this paper.

I will follow Ohtani and Hisasaka's inclusive definition of metacognition (2018), encompassing, but not entirely separating, two broad sub-categories:

(1) Metacognitive knowledge: including understanding of cognition, knowledge of which strategies to use, and when (Zohar & Barzilai, 2013).

(2) Metacognitive skills (sometimes 'metacognitive activities'): focussing on monitoring and controlling cognition, including planning, monitoring, and evaluating one's use of strategies (Schraw et al., 2006).

This definition shares themes with many researchers' stances, even where overarching theoretical frameworks disagree. For example, it reflects Flavell's original (1979) categories of metacognitive knowledge and monitoring skills, as well as Schraw et al.'s (2006) division of metacognition into the 'knowledge' and 'regulation' of cognition. Furthermore, this definition of metacognition relates to many types of thinking – including, but not limited to, problem-solving (as focussed on by Zepeda, Richey, Ronevich & Nokes-Malach, 2015), but also knowledge / processes relating to development of a conceptual system (sometimes termed 'metaconceptual' thinking, e.g. Yuruk et al., 2009).

From here, I define metacognitive strategies. As with metacognition, this term does not see consistent use. For example, Pintrich and de Groot's (1990) articulation of metacognitive strategies – relating to "planning, monitoring, and modifying… cognition" (p.33) – closely aligns with my earlier description of 'metacognitive skills'. They find overlap with Flavell's (1979) early work where metacognitive strategies relate to cognitive monitoring, including "surveying all that you have learned to see if it fits together into a coherent whole" (p.909). In contrast, some reject the phrase entirely, as with Schraw et al. (2006), who instead group together regulation, evaluation and reflection on learning within 'problem solving strategies' and 'critical thinking strategies'. The lack of an agreed classification of metacognitive strategies is acknowledged by Perry et al. (2019) who attribute this to the field's 'fuzzy' nature. In response, they choose an inclusive definition – one I will follow – grouping all practical strategies that "seek to equip pupils with an increased understanding of how to learn, as opposed to… knowledge specific to a subject domain" (p.485). The authors include any process that supports use of the (more general) metacognitive skills of planning, monitoring and evaluation, alongside explicitly naming strategies beneficial for developing students' problem-solving, such as using writing frames or creating mind/concept maps.

How do metacognitive strategies impact learning in science?

Numerous studies have linked use of metacognitive strategies with improved academic performance (Perry et al., 2019; Pintrich & de Groot, 1990). These correlations persist even when 'controlling for intelligence' – typically achieved in previous studies by using 'intelligence quotient' measures derived from tests of factors such as reasoning, verbal ability and memory, as in Veenman and Beishuizen's (2004) research into the text-studying performance of 46 Dutch social-sciences students and Ohtani and Hisasaka's (2018) meta-analysis of 118 peer-reviewed articles. This seeming independence from 'intelligence' does support the assertion that metacognition is a real, independent factor. We might, however, reasonably ask how far we can generalise from these studies, which are commonly laboratory-based and, as with Veenman and Beishuizen's (2004) work and most of Ohtani and Hisasaka's (2018) samples, recruit adult volunteers (often university students). What role does metacognition play in secondary schools, and how might we exploit this to support students' learning in science?

To answer this, we can look to the systematic research review of Zohar and Barzilai (2013), which identifies metacognition as being of significant interest within science education research, with strong links to scientific conceptual understanding. Although this review is over eight years old, it provides useful insight into the nature and extent of research in the field. Zohar and Barzilai systematically searched peer-reviewed articles from the period 2000-2012, indexed in the ERIC education research database and various additional science education journals. With 178 studies explicitly referencing metacognition and focusing on science education, the authors identified a significant recent expansion in the research field (from under five studies annually in 2000-2003, increasing to 35 in 2012). Moreover, from thematic analysis of abstracts and full-text reviews of the 66 studies that assessed metacognitive interventions, the researchers concluded that "conceptual understanding is one of the hot areas of current science education metacognition research" (Zohar & Barzilai, 2013, p.147), identifying ‘content knowledge’, ‘conceptual understanding’ and ‘science concepts’ commonly featuring amongst studies’ constructs of interest. These results broadly confirm metacognition to be a promising avenue for supporting conceptual learning in science. However, despite the study’s rigorous approach for analysing research trends, its lack of consideration of studies’ actual findings prevents further conclusions: just because there has been a growth in research into metacognitive strategy instruction, this does not guarantee that there has been a parallel growth in evidence for its efficacy.

In contrast, support for the impact of metacognition on classroom-based physics learning comes from Zepeda et al.’s (2015) quasi-experimental study of 46 US students aged 13-14. Across four weeks, students completed six hours of self-guided activities of either a control or experimental condition. Whereas the control group spent this time purely on force and motion practice questions, the experimental group’s work was interleaved with written metacognition guidance and written prompts of metacognitive skills (planning, monitoring and evaluating). The intervention’s impact was assessed through student surveys and pre/post conceptual understanding tests (the well-established Force Concept Inventory (FCI) of Hestenes, Wells, & Swackhamer, (1992)). Overall, students receiving the metacognitive instruction not only outperformed the control group when problem solving (despite receiving less practice over the lesson sequence) but also showed greater conceptual understanding gains. This result points to the potential power of classroom-based metacognitive support, although the homogeneity and small size of the study’s sample (only 46 students, all taken from the same academic year of one US middle school) leaves room to query the findings’ replicability elsewhere or with older students – with the researchers positing that similar interventions may be less effective once students had “reached a plateau” in metacognitive development (Zepeda et al., 2015, p.968).

Other research, however, reinforces these findings. For example, Yuruk et al. (2009) worked with a similarly-sized group of US students (n=45) in a quasi-experiment introducing metacognitive activities to a randomly-selected intervention group. These activities – including poster drawing, journal writing, concept mapping and group discussion – focused on metaconceptual skills, encouraging students to reflect on their understanding, monitor their ideas, and evaluate competing explanations. As with Zepeda et al. (2015), this study focused on force and motion concepts, using the FCI (Hestenes et al., 1992) to compare students’ conceptual understanding pre- and post-intervention (Yuruk et al., 2009). The results similarly showed that the experimental group displayed stronger performance on conceptual understanding tests, with this persisting even after nine weeks. Furthermore, through qualitative analysis of students' work, journal entries and lesson contributions, the authors theorised that:

> "Individuals who monitor the changes in their ideas are less likely to use their previous conceptions, as this monitoring process has a capability to generate information about the validity of their current and previous ideas, as well as their justifications for the changes in their ideas."
>
> (Yuruk et al., 2009, p.472)

These findings offer indications of how metacognitive strategies might directly enhance conceptual learning. Furthermore, this focus on students aged 16-18 (incidentally also the age range of this study's Year 12 group) supplies evidence that metacognitive interventions may indeed help older learners.

Despite these studies' powerful results, they paint a limited picture – each based only on students in the US education system. Furthermore, they focus solely on force and motion concepts, offering no direct support for efficacy with other physics topics. However, research into thermal physics concepts offers us confidence here. For example, Harrison et al.'s (1999) review (referenced earlier) specifically emphasises how the resistance of alternative conceptions in thermal physics increases the importance of "strategies which cause the students to repeatedly examine their beliefs" (p.59) and specifically recommends concept mapping for consolidating valid connections between often-misunderstood concepts (e.g., heat and temperature – see Table 1 above).

In summary, research interest in metacognition's impact on conceptual understanding is currently growing (Zohar & Barzilai, 2013), with school-based quasi-experimental studies finding that students' understanding of force and motion concepts may be boosted by explicitly encouraging use of metacognitive strategies (Yuruk et al., 2009; Zepeda et al., 2015). This, therefore, provides strong grounds to explore whether similar approaches may help to overcome the common conceptual challenges of thermal physics. With this, I will therefore next explore how metacognitive strategies can be taught, as well as the potential challenges of ascertaining their impact.

How can metacognitive strategies be taught?

As suggested above, it is commonly recognised that metacognitive knowledge and skills can be actively developed through instruction (Dignath & Büttner, 2008; EEF, 2019; Perry et al., 2019).

Such a conclusion is supported by laboratory-based studies such as that by Veenman and Beishuizen (2004), who additionally argue that metacognitive instruction should be embedded within the relevant learning context (such as the studies in the subsection above teaching metacognitive strategies as applied to physics lessons and content). However, for a more comprehensive overview of approaches to teach metacognitive strategies within science education, the systematic literature review of Zohar and Barzilai (2013) again offers insight. For their coding of studies, the authors developed a classification of methods of metacognitive instruction (defined as anything including "specific and explicit metacognitive activities" (p.136) – matching my chosen inclusive definition of metacognitive strategies presented earlier). Their resulting framework (Table 2) ranges from explicit instruction through to teacher-led modelling of metacognitive strategies and, importantly, directly accommodates the examples from the earlier subsection on how metacognitive strategies impact learning (Zepeda et al.'s (2015) metacognitive prompting corresponding to (c), whilst Yuruk et al.'s (2009) metaconceptual journaling, poster drawing, discussion and concept mapping relate to (d-f) and (h)).

Metacognitive instruction approach	Description
(a) Explicit instruction	Visible and explicit teaching of metacognitive knowledge and skills.
(b) Practice and training	Repeated practice of applying metacognitive knowledge and skills in tasks, problems and contexts.
(c) Metacognitive prompts	Provision of written questions or cues (e.g., in writing, by the teacher, by other students) to foster metacognitive thinking.
(d) Teacher-led metacognitive discussions	Teachers talking with their students about their thinking and learning to encourage metacognitive thinking.
(e) Student-led metacognitive discussions	Discussions led and managed by learners, often with structuring, to support metacognitive thinking.
(f) Metacognitive writing	For example, the use of journals or reports to encourage learners to reflect on, describe and analyse their thinking and learning.
(g) Metacognitive modelling	Teacher demonstrations of activating and applying metacognitive knowledge and skills in the course of learning.
(h) Concept mapping and other visual representations	Use of concept maps, graphic organisers, flow-charts and other visual representations to support learners to represent and share their thinking and learning.
(i) ICT use for metacognitive instruction	Use of digital information and communication technologies to facilitate teaching or facilitation of metacognition.

Table 2: Overview of common approaches for teaching metacognitive strategies within science education

Adapted from Zohar and Barzilai (2013)

Whilst researchers have identified multiple approaches for teaching metacognitive strategies, methods for evaluating their use are undermined by metacognition's inherently 'implicit' nature – both the fact that metacognition is internal to an individual and therefore impossible to observe externally, but also that it is frequently subconscious, operating without the awareness of the individual themselves (Akturk & Sahin, 2011). Researchers often employ questionnaires such as the Motivated Strategies for Learning Questionnaire (MSLQ) (Pintrich, Smith, Garcia & McKeachie, 1991) or the Metacognitive Awareness Inventory (MAI) (Schraw & Dennison, 1994) to assess students' awareness and use of metacognitive knowledge and skills. However, the validity of using students' self-reports has been questioned, with some noting that these are poorly correlated with other measures (Zohar & Barzilai, 2013). Various researchers distinguish between 'off-line' measures (those taken asynchronously with learning, e.g., questionnaires or interviews) and 'on-line' measures (synchronous with learning, e.g., think-aloud protocols – where learners narrate their thoughts), with Ohtani and Hisasaka (2018) suggesting that off-line measures are less accurate, potentially because self-reporting typically only probes students' domain-general metacognitive skills, rather than those relating to specific tasks. Practical studies report similar challenges, such as in Zepeda et al.'s (2015) evaluation of metacognitive prompting in which no increase was seen in students' self-reported use of metacognitive skills (via the MAI) despite the apparent impact of metacognitive instruction on conceptual understanding and problem-solving. Authors attributed this disparity to the inherent limitations of metacognition questionnaires, suggesting that students may well be unaware of their use of metacognitive skills. These observations present significant epistemological challenges for research into metacognitive strategy instruction. As Zohar and Barzilai (2013) note, teaching of metacognitive strategies tends to overlap with other pedagogical interventions (e.g., collaborative learning, problem-solving and inquiry learning) – hence, if benefits are observed for learning but no such shift is seen in indicators of metacognition, it becomes unclear as to whether any part of these benefits can truly be attributed to the metacognitive strategies alone.

Summary

In summary, thermal physics presents students with numerous conceptual challenges, with many proving resistant to traditional instruction (Clough & Driver, 1985). Researchers suggest that these challenges may, in part, arise from students not recognising generalisations between ideas (Yeo & Zadnik, 2001), or from students not consciously monitoring and evaluating their learning (Harrison et al., 1999). This, coupled with positive findings from research into teaching of force and motion concepts (Yuruk et al., 2009; Zepeda et al., 2015), provides a reasonable basis for exploring how metacognitive strategies may support students' thermal physics learning. Finally, whilst various approaches have been identified for the teaching of metacognitive strategies (defined here as those supporting the skills of planning, monitoring, evaluation and regulation of thinking and learning), there remain unresolved methodological challenges associated with their assessment, stemming primarily from metacognition's implicit nature, and the limitations of students' self-reports.

My literature review therefore leads me to explore the following research questions, which allow incremental evaluation of the intervention activities, their impact on students' metacognitive skills, and any accompanying impact on conceptual learning:

> RQ1: To what extent does teaching of specific metacognitive strategies support Y12 students to implement them?
>
> RQ2: To what extent does teaching of specific metacognitive strategies impact Y12 students' metacognitive skillsets?
>
> RQ3: To what extent does use of specific metacognitive strategies support Year 12 students' conceptual understanding of thermal physics?

Methodology and methods

Methodology: action research

In the preceding section, I described how this study's motivation stems from the need to overcome various well-described challenges associated with learning thermal physics concepts. As such, this project adopted an 'action research' methodology, an approach described as "applied research, carried out by practitioners who have themselves identified a need for change or improvement" (Bell, 2006, p.8). As Denscombe (2017) describes, this methodology is defined by a practical focus on real-world problems, its instigation of change, the participation by practitioner-researchers, and its cyclical nature whereby findings inform future changes (as illustrated in Figure 1).

This methodological choice not only allows more direct assessment of the impact of metacognition on conceptual understanding than other, potentially more passive methodologies (e.g., case study or ethnography), but also suits the local context of my research.

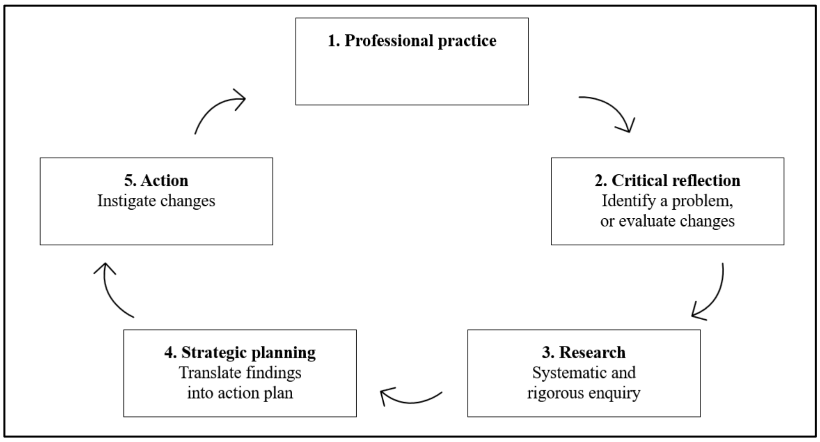


Figure 1: The cyclical process of action research

redrawn from Denscombe (2017, p.129)

This local focus also introduces benefits: with teachers piloting changes within their own practice, action-research studies benefit from a practitioner's considerable insider knowledge and, in turn, offer powerful benefits for that teacher's professional development (Denscombe, 2017). However, action research's local focus also presents disadvantages, namely risks of bias (with practitioner-researchers inevitably holding vested interests in findings), small sample sizes limiting generalisation to other contexts, and the extra workload imposed upon the main teacher-researcher sometimes preventing optimal implementation or rigorous evaluation (indeed workload and time constraints here restricted this study to only one iteration of Figure 1's cycle, itself limiting the study's potential for driving significant improvement) (Denscombe, 2017).

Teaching context

Overview

This study took place across five one-hour lessons with Year 12 physics students (aged 16-17) at a UK mixed-gender secondary school. The school, a non-selective comprehensive academy of around 1,300 students aged 11-18, has a diverse catchment spanning both suburban and rural areas. The class studied was the school's only Year 12 physics class, and consisted of just six students, all male. The chosen interventions took place within lessons taught by myself, the author, covering the AQA physics A-level topic of 'Thermal energy transfer' (section 3.6.2.1 within AQA, 2017, p.32), which covers internal energy, thermal energy transfer, specific heat capacity and state changes – topics which correspond closely to the heat and temperature-focused conceptual challenges of Table 1.

Lesson sequence and interventions

Table 3 (next page) summarises the five-lesson sequence, including overviews of each lesson's metacognitive interventions (described further below) and data-collection methods. It should also be noted that these lessons, held across four weeks in early 2021, were affected by the UK's ongoing COVID-19 public health measures, and therefore featured a mix of face-to-face and virtual teaching (via Microsoft Teams).

a) Concept mapping and reflection:

In lessons 1 and 4, students worked iteratively on concept maps:

(1) **Lesson start: students produce node-link maps.** Students spend ten minutes linking key terms with labelled arrows, with the teacher having modelled an example map (for another concept) in lesson 1.

(2) **Lesson close: students update and reflect on their maps.** Using a differently coloured pen, students update their map. Finally, students write an evaluative comment (e.g., describing a shift in their understanding, or an area of conceptual uncertainty).

This approach mirrored the concept mapping activities of Yuruk et al. (2009), offering students some freedom of map design and choice of terms (see Figure 2 below), although it lacked opportunities for collaboration (not practical during virtual lessons) – something that may have reduced students' opportunities for reflection. The later updating step served to encourage consolidation of new concepts, as advocated in Harrison et al.'s (1999) review of thermal physics conceptions and linked to deepening understanding (Romance & Vitale, 1999). Finally, the evaluation step aimed to emulate Yuruk et al.'s journal-writing activities to encourage metaconceptual reflection (2009), although the approach here is clearly more limited (versus long-form journal entries) whilst being equally at risk of students' writing being "restricted… to brief descriptive statements" (p.464).

Lesson (or event)	Lesson format (no. of students attending virtually vs in-person)	Intervention implemented		Data collection methods				
		Concept mapping and reflection	Planning and evaluation of problem-solving	Metacognition survey	Collection of student work	Exit tickets	Conceptual understanding test	Focus group interview
End of previous lesson: project introduction	*Virtual: 6* *In-person: 0*	*N/A*	*N/A*	✓				
Lesson 1: Internal energy & energy transfer	Virtual: 6 In-person: 0	✓ Five prompt words (internal energy, temperature, heat, average kinetic energy, potential energy)			✓ *(Concept map)*	✓		
Lesson 2: Specific heat capacity	Virtual: 0 In-person: 6		✓			✓		
Lesson 3: Specific heat capacity practice	Virtual: 5 In-person: 1		✓		✓ *(Problem solving from lessons 2-3)*	✓		
Lesson 4: Latent heat	Virtual: 5 In-person: 1	✓ Five prompt words (temperature, phase change, latent heat, kinetic energies, potential energies)			✓ *(Concept map)*	✓		
Lesson 5: Synoptic practice and end-of-sequence conceptual test	Virtual: 0 In-person: 6		✓	✓			✓	
Voluntary focus-group interview after project	*Virtual: 0* *In-person: 4*	*N/A*	*N/A*					✓

Table 3: Overview of the lesson sequence, interventions and data collection methods used

Also included are events before and after the lesson sequence in which the project was introduced and/or data collection occurred

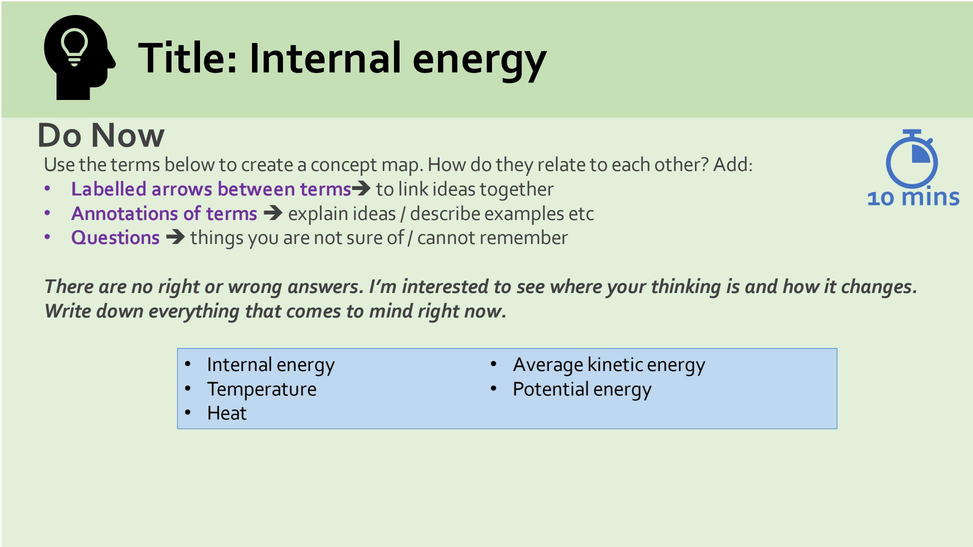


Figure 2: Slide of guidance for the concept mapping activity used at the start of lesson 1

b) Planning and evaluation of problem-solving:

During lessons 2, 3 and 5, students practised quantitative problem-solving whilst explicitly reflecting on their approach:

(1) **Before question: write plan.** Students were instructed to write brief descriptions of their problem-solving plan, e.g. noting relevant assumptions / principles, or relating the question to one seen before.

(2) **After question: reflection.** E.g. a written comment on whether their plan had worked, whether they were confident in their answer, or if they would adopt a different approach next time.

As with the concept mapping, I initially modelled this activity for students, later employing it when completing worked examples. The activity sought to emulate Zepeda et al.'s (2015) prompting of metacognitive skills, albeit adopting a significantly less intensive approach. For example, the opportunities for problem solving here typically lasted 10-20 minutes, much less than the eight 45-minute sessions in Zepeda et al.'s study. Additionally, prompts were only issued verbally, in contrast to Zepeda et al.'s printed packets of written guidance, examples and prompts. Whilst this simpler approach was necessitated by time constraints, the resulting intervention was clearly limited and therefore might be expected to yield reduced student engagement, or less considered student reflections.

Evidence collection methods

Students’ engagement with the intervention activities, their reflections on their learning and measures of their conceptual understanding were monitored throughout the study (see Table 3). With the study lacking a comparison group due to the small sample size and action research methodology, multiple sources of both qualitative and quantitative evidence were identified for each research question (see Table 4, and more detail on each method below). The use of multiple evidence-collection methods allowed cross-checking – or *triangulation* – of findings, enabling confirmation or challenge of possible conclusions (Bell, 2006). In Table 4 a bracketed tick "(✓)" indicates where a source is not a primary data collection method, but provides an opportunity for triangulation of findings from other sources.

Research question	Metacognition survey	Students' work	Exit tickets	Conceptual understanding test	Focus group interview
RQ1: To what extent does teaching of specific metacognitive strategies support Y12 students to implement them?		✓	✓		✓
RQ2: To what extent does teaching of specific metacognitive strategies impact Y12 students’ metacognitive skillsets?	✓	(✓)	✓		✓
RQ3: To what extent does use of specific metacognitive strategies support Year 12 students’ conceptual understanding of thermal physics?		(✓)	✓	✓	✓

Table 4: Summary of data collection methods mapped to the relevant research question(s)

Metacognition survey

A survey was deployed before and after the lesson sequence to track students’ self-perceptions of their metacognitive processes. Questions were drawn from the “Self-Efficacy and Metacognition Learning Inventory–Science”, or SELMLI-S, in which students report how often they use various skills (Thomas, Anderson & Nashon, 2008). This questionnaire was originally developed for high-school science settings and was piloted with 465 Hong Kong students aged 13-18, providing evidence for its replicability and construct validity (Gascoine, Higgins & Wall, 2017). Two subscales were used:

(1) **Constructivist Connectivity:** assessing if students make links between concepts (chosen for its relevance to 'concept mapping').

(2) **Monitoring, Evaluation & Planning:** assessing students' use of these metacognitive skills (linked to the 'planning and evaluation of problem solving' activity).

Results were analysed via simple tabulation, as the small sample undermines use of inferential methods.

The questionnaire's focus on high school science made its use here more appropriate than other (potentially more prominent) questionnaires such as the aforementioned MAI or MSLQ, which were developed to assess undergraduates' general learning (Pintrich et al., 1991; Schraw & Dennison, 1994). However, the SEMLI-S was not perfectly matched to this project, having been developed for Hong Kong schools, and science in general – necessitating edits to focus on physics specifically, as some students also attended chemistry lessons (see final questionnaire in Appendix 1). Finally, the questionnaire's consistency and reliability were enhanced by using an online Microsoft Forms survey for both pre- and post-test.

Students' work

After each intervention activity ('concept mapping' or 'planning and evaluation'), students submitted digital photos of their work. This provided direct indications of students' success in implementing the activities, but also qualitative data with which to triangulate other findings (e.g., regarding students' metacognitive reflection). As Taber notes, students' work can only ever provide indirect evidence of their thinking, since "answers may reflect what the learners think they are meant to write, rather than what they actually think or believe" (Taber, 2013, p.263). These data sources were analysed qualitatively, with some simple categorisation and analysis of students' implementation of the activities (see Appendix 2).

Exit tickets

Short digital "Exit ticket" surveys were used at the end of lessons 1-4 to probe students' conceptual understanding, reflections on learning, and experience of the intervention. As encouraged by Denscombe (2017), these questionnaires were kept as short as possible to maximise completion rates and lessen the risk of questionnaire fatigue. Both open and closed questions were used (see Appendix

3), with each survey featuring two brief conceptual questions – often multiple choice – alongside questions on the intervention activity's feasibility and perceived effectiveness, both of which employed scaled responses. Finally, as recommended by Marzano (2012), each survey included a voluntary opportunity for open comment and communication to the teacher regarding the interventions – both providing a source of additional qualitative information, and encouraging students' honesty. As with the metacognition survey, the administration of the survey was kept consistent throughout, adopting the Microsoft Forms platform.

Conceptual understanding test

To assess conceptual understanding, students sat multiple-choice tests in the final lesson. Questions were sourced from the Thermal Concept Evaluation, TCE, (Yeo & Zadnik, 2001) and Thermodynamic Concept Survey, TCS, (Wattanakasiwich et al., 2013) alongside four additional questions (see Appendix 4). The validity and reliability of the TCS and TCE have been repeatedly assessed. Each test has been independently evaluated by experienced physicists to establish their content validity (that they adequately sample the relevant concepts) and face validity (that they measure what they intend to), as well as undergoing extensive trials – with the TCE piloted on 478 high school and university students in Western Australia and the TCS on over 2000 Thai and Australian university undergraduates – showing both to be capable of distinguishing between 'expert' and 'novice' conceptual understandings, thereby establishing construct validity. Whilst the final test used here offers quantitative results, caution should be adopted in its analysis: direct comparison of results is not possible (this study has neither a control group, nor was it appropriate to compare against a pre-project survey, which would have tested students' conceptual understanding before any teaching at all – thereby preventing isolation of the impact from the teaching of metacognitive strategies alone).

Focus group interview

After the sequence, a voluntary 45-minute focus group interview was held to explore students' experiences. The focus group format was selected to encourage interaction and sharing of perspectives, thereby capitalising on this format's power for generating insights into "how people think about an issue… why they hold the views they do" (Laws, Harper & Marcus, 2003, p.299). Questions were open and straightforward, seeking descriptive answers first before delving into explanations (Laws et al., 2003). Due to the small class size an ‘opportunity sampling’ approach was adopted (i.e., interviewing those willing and able to attend), resulting in a group of four. To avoid excluding certain individuals, an interview time was chosen that aligned with all students’ school timetables. During the interview, I sought to minimise the risk of one individual’s views dominating (Bell, 2006); this was achieved via periodic checks of each individual’s thoughts (along the lines of “[Student A], would you agree or disagree with that?”). Detailed interview notes were captured and analysed qualitatively, with responses coded against the research questions. Later in this report, qualitative data are presented from the focus group interview (and from students’ exit ticket responses), with each quote attributed to a pseudonym (each individual student was numbered randomly as S1, S2, … S6).

Ethics

I developed the project plan in line with recommendations from Bell (2006) and British Educational Research Association guidance (BERA, 2018). The class teacher, school professional tutor and Faculty subject lecturer were consulted on the project’s design and their approval obtained for it to proceed. All interventions were designed to avoid knowingly detrimental effects on student progress. Students were briefed on the project before the first lesson and written permission was obtained from parents/carers to allow use of anonymised data. Throughout, students and parents/carers were informed that they may withdraw consent or participation, without the need for any explanation. Whilst this clear communication of intentions and seeking of informed consent is crucial for the integrity of practitioner research, it is worth considering the potential impact on students, especially regarding the known potential for participants to (deliberately or implicitly) change their behaviour in response to observation (Taber, 2013).

Analysis and discussion

In these sections I will address each research question in turn, initially presenting quantitative results followed by triangulation with qualitative evidence and broader discussion, including comparison to existing research.

RQ1: To what extent does teaching of specific metacognitive strategies support Y12 students to implement them?

Exit tickets

The end-of-lesson "Exit ticket" surveys provide insight into students' perceptions of the ease of implementing the proposed metacognitive strategies using the intervention activities. After each lesson, students rated that day's intervention activity according to how straightforward it seemed (e.g., 1="very difficult", 3="neither difficult nor easy", 5="very easy"). This produced two scores (each activity was carried out in two lessons with exit tickets). These, plus scores from an identical end-of-project survey, were pooled yielding the results in Table 5.

Activity	Total number of responses	Average score out of 5	Percentage of scores >4 ("Quite easy" or "Very easy")
Creating a concept map at the start of the lesson	15	3.2	40%
Updating and reflecting on your concept map	15	3.9	87%
Reflecting on your problem-solving approach when doing questions	15	3.5	60%

Table 5: Students' ratings of the ease of completing the metacognitive intervention activities

Students' work

Students' submitted work (concept maps and problem-solving) allows insight into students' engagement with the activities. Although return rates for students' work fell below 100% (partly hampered by the challenges of collecting work during remote learning), all submitted work was reviewed and categorised according to the style of completion. Results are summarised in Table 6, with the categorisation explained further in Appendix 2.

Discussion

Table 5 shows that students' average difficulty rating for each intervention activity was above 3 (the score for "neither difficult nor easy"), suggesting that – overall – the class perceived them to be feasible. The higher scores indicate activities with lower perceived difficulty, with students reporting that updating or reflecting on concept maps (at the end of lessons) was more straightforward than developing them initially. Whilst these numerical scores offer only limited insight into students' experiences, these findings were supported by the focus group:

> *"The first time we did the concept mapping, I hadn't done the topic for ages, so it didn't feel so helpful." (S1)*
>
> *"I remember seeing it [concept mapping prompts] at the start, I wrote for a minute or two and then I was completely out. But reviewing it at the end of the lesson, I was able to add more and get it into a note form." (S2)*

Criteria for categorising work	**Number of pieces of work**		**Comments on work not meeting criterion**
	✓ **Criterion met**	✗ **Criterion not met**	
Concept mapping and reflection – lesson 1			
Prompted words included in map with nodes and labelled links	2	2	1 × "typical mind-map" format 1 × "list of definitions" format
Map updated at end of lesson	4	0	
Written reflective comments	0	4	4 × work without reflective comments
Problem solving planning and evaluation – lessons 2 + 3			
Algorithmic steps included in initial plans	3	1	1 × submission with no written plans
Conceptual understanding included in initial plans	0	4	4 × no reference to conceptual principles
Written evaluative comment reflecting on conceptual understanding included	2	2	1 × basic comments on problem-solving steps 1 × no evaluative comments seen
Concept mapping and reflection – lesson 4			
Prompted words included in map with nodes and labelled links	3	2	2 × "lists of definitions" format
Map updated at end of lesson	4	1	1 × map without updates
Written reflective comments	3	2	2 × work without reflective comments

Table 6: Summary of categorisation of student's work, for each lesson activity

However, triangulating these findings with students' submitted work urges some caution. From the examples of work received (Table 6) we see that students did not always complete the intervention activities as envisaged. For example, only around half of the concept maps adhered to the node-link format that I had demonstrated, with others showing unlabelled links or written statements. One explanation for this was suggested by the focus group, with students commenting that the concept mapping activity felt new, but that it most closely resembled techniques of mind-mapping that they had employed when revising to give "a whole overview of a topic, to provide summary notes" (S3). Similarly, the submitted planning and evaluation activity work contained, at most, only brief plans and reflections, concentrating mostly on algorithmic calculation steps (e.g., "Use Watt equation for energy, use $\Delta Q = mc\Delta\theta$, take copper from total to get liquid" (S3)). This was reflected in students' focus group comments, with some reporting challenges (e.g., "I couldn't write the plan down without actually doing the question" (S1)), reluctance to complete the additional writing (e.g., "I always just have it in my head. The planning was just time-consuming" (S3)), and with focus group reflections showing a similar tendency towards algorithmic problem solving rather than the application of physics principles (e.g., "Normally you just read the question and see 'I need to use specific heat capacity' so I don't usually write the plan out" (S1)).

This variability in metacognitive activity completion is consistent with previous studies (Moser, Zumbach & Deibl, 2017), and is also perhaps expected given this study's short duration. The lesson sequence allowed at most 20 minutes per lesson for instruction and practice of the chosen skills, significantly less than examples in the literature – take, for example, Zepeda et al.'s (2015) metacognitive prompting, which devoted six hours to students completing "scaffolded… [question] packets, with instruction of metacognitive skills interwoven with… practice" (p.968). Other studies similarly report how activities requiring students to write down their problem-solving strategies require significant support and encouragement, with researchers initially facing "complaints… that strategy writing was difficult and that it required considerable effort" (Leonard, Dufresne & Mestre, 1996, p.1502). Another possible reason for students' reticence towards metacognitive reflection during problem solving arises from how this differs from what is apparently required for exams and assessments – as echoed by Thomas (2013) who describes how some students considered their new metacognition-focused lesson activities to be "not useful in the context of what can be considered as mandated, culturally mediated assessment tasks" (p.1202). Similarly, the limited sophistication of students' problem-solving plans and reflections may represent a commonly-documented feature of more 'novice' problem-solving styles, in which individuals attempt to match formulae to questions, rather than applying consistent physics principles (Reif & Heller, 1982). It is understandable that, without support to adopt more sophisticated problem-solving strategies, writing out one's plans might feel unhelpful and redundant. If so, we may expect that the problem-solving planning and evaluation activity might, in future, benefit from more explicit scaffolded support and instruction of problem-solving and its associated metacognitive skills – a conclusion that is consistent with previous studies (Veenman & Beishuizen, 2004; Zepeda et al., 2015).

In summary, the teaching intervention appears to have achieved modest success in supporting students to implement the chosen metacognitive strategies. Whilst there was significant variability in submitted work, students reported feeling confident across all activities, and several students did show evidence of producing written problem-solving plans, labelled node-link concept maps and, importantly, subsequent reflection on these. From comparison with previous studies, it appears that students would have benefited from more instruction and practice of these strategies, which students described as unfamiliar. Finally, due to metacognition's tacit nature, any success in completing the activities should not be taken as evidence for or against their effectiveness. For this, I must consider my other research questions: relating to students' metacognitive skillsets and conceptual understanding.

RQ2: To what extent does teaching of specific metacognitive strategies impact Y12 students' metacognitive skillsets?

Metacognition survey

The pre/post survey offers only weak evidence of the intervention driving a shift in students' use of metacognitive skills. Table 7 (next page) presents the results of the metacognition survey pre and post intervention (see also Appendix 1 for more detail). Students rated statements on scale of 1-5 according to how often they carried out each activity.

Discussion

Due to the small sample size, the observed shifts in students' metacognition survey scores can only be taken as indicative. However, reviewing all statements, three stand out (7, 10, 15) – with sizeable shifts in both average score and percentage of responses at ≥4 (a score corresponding to using that skill over half the time). Positive shifts are seen for statement 7 ("I seek to connect what I learn in my life outside of class with ideas in my Physics lessons") and 10 ("I consider whether or not a plan is necessary for a learning task before I begin that task"). This is perhaps unsurprising, since these skills form the foci of the intervention activities themselves (the 'connecting' element of 7 relating to concept mapping, and the 'planning' element of 10 matching the problem-solving planning activity). On triangulation, qualitative reflections support the positive impact of concept mapping:

"it was helpful to see what new links we can make between older topics we have covered" (S4, exit ticket)

"I was able to connect my thoughts together at the start, and then secure my knowledge by finishing links" (S1, exit ticket)

"The concept maps helped to connect the ideas together as we went through the topic." (S3, focus group)

#	Statement	Change pre- to post-project	
		Class- average score	% of responses ≥ 4
Large positive change:			
7	I seek to connect what I learn in my life outside of class with ideas in my Physics lessons.	+0.8	+60%
10	I consider whether or not a plan is necessary for a learning task before I begin that task.	+1.0	+60%
Large negative change:			
15	I assess how much I am learning during a learning task.	-1.2	-40%
No clear change:			
1	I seek to connect what I learn from what happens in Physics lessons with out-of-class science activities (e.g., field trips, science visits, documentaries).	+0.2	0%
2	I adjust my plan for a learning task if I am not making the progress I think I should.	+0.4	0%
3	I seek to connect what I learn from out-of-class science activities with what happens in Physics lessons.	+0.2	+20%
4	I plan to check my progress during a learning task.	-0.8	0%
5	I try to understand clearly the aim of a task before I begin it.	0.0	0%
6	I evaluate my learning processes with the aim of improving them.	+0.2	0%
8	I consider what type of thinking is best to use before I begin a learning task.	0.0	0%
9	I seek to connect the information in Physics lessons with what I already know.	0.0	0%
11	I seek to connect what I learn from out-of-class science activities (e.g., field trips or science museum visits) with what happens in Physics lessons.	0.0	+20%
12	I stop from time to time to check my progress on a learning task.	0.0	+20%
13	I try to predict possible problems that might occur with my learning.	0.0	-20%
14	I seek to connect what I learn from what happens in the Physics classroom with out-of-class science activities.	+0.2	0%
16	I seek to connect what I learn in other subject areas with Physics.	+0.4	+40%

Table 7: Comparison of metacognition survey scores pre- vs post-project

This is consistent with the literature, for example Nesbit and Adescope's meta-analysis of concept mapping research references Larkin and Simon (1987) to suggest that concept maps' visual integration of propositions "may lower the cognitive load needed to add new associations" (Nesbit & Adesope, 2006, p.418). Therefore, I am inclined to conclude that the concept mapping activity contributed to the shift in students' awareness and monitoring of their conceptual knowledge, although I cannot assess if this would be sustained long-term, owing to the study's short duration.

Students' reflections, however, offer little evidence for positive impacts on metacognitive skills from the planning and evaluation activity. Focus group participants described how "writing the plan was less helpful" (S1), whilst others spoke only hypothetically of any benefit: "writing out the plan could help with the thought process… for some people" (S4). There is an absence of similar positive shifts for other planning-related statements in the metacognition survey (e.g., 5, 8, 13), and a sizeable negative shift related to metacognitive monitoring in statement 15 ("I assess how much I am learning during a learning task"). Therefore, it appears the intervention may have encouraged students to "consider whether or not a plan is necessary" (in the words of statement 10), but not delivered a meaningful boost for the broader skills of planning, monitoring and evaluation. Indeed, omitting an explicit intervention activity for 'monitoring' may have inadvertently led to students devaluing this skill. This apparent absence of positive impacts is not inconsistent with research. As previously acknowledged, this study devoted considerably less time to these metacognitive skills than previous studies (Yuruk et al., 2009; Zepeda et al., 2015). Previous researchers have warned against this, noting how positive long-term results rely upon students being "instructed for a prolonged period" (Veenman & Beishuizen, 2004, p.635).

In summary, concept mapping may have, even if only in the short-term, encouraged students' attempts to interlink their knowledge – a process requiring metacognitive (or metaconceptual) awareness and reflection (Yuruk et al., 2009). Conversely, there is little evidence for the 'problem-solving planning and evaluation' activity positively impacting on students' metacognitive skills, possibly due to the intervention's brevity and lack of scaffolding. Next, I assess whether completing these activities, and the potential accompanying subtle shift in students' metacognitive skills, may have supported students' conceptual understanding.

RQ3: To what extent does use of specific metacognitive strategies support Year 12 students' conceptual understanding of thermal physics?

Conceptual understanding test

Results from the end-of-project conceptual test are summarised in Figure 3. This figure shows the class' overall performance on each question of the conceptual test (blue), overlaid with comparative scores from several previous studies that used the TCE and TCS tests (see key on chart). The previous studies used were: Greek data from Stylos, Sargioti, Mavridis and Kotsis (2021); Turkish data from Adadan and Yavuzkaya (2018); Australian data from Wattanakasiwich et al. (2013).

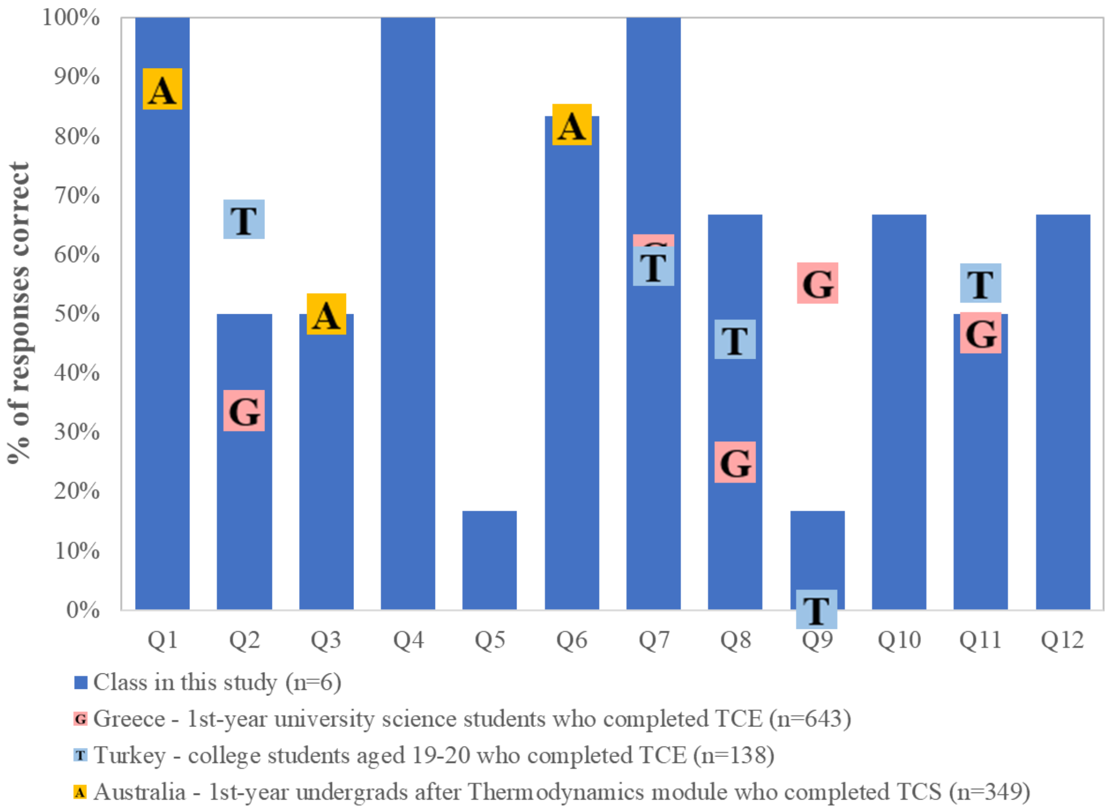


Figure 3: Summary of the class' conceptual understanding test performance and comparison with other published studies

Clearly misconceptions are prevalent amongst the students even after the lesson sequence, as several questions elicited incorrect responses. These conceptual difficulties were not restricted to one area; for example, whilst both Q4 and Q5 relate to internal energy and temperature, these yielded both the test's joint-highest and joint-lowest scores. Despite this, when compared against scores from (mostly older) groups of students in previous studies (Adadan & Yavuzkaya, 2018; Stylos et al., 2021; Wattanakasiwich et al., 2013), the proportions of correct responses from this class appear neither systematically lower nor higher (see Figure 3). Although the class size (six) is too small to allow detailed comparison of scores versus these other studies, it does seem reasonable to conclude that the class's understanding is not dramatically better or poorer than groups studied previously.

Discussion

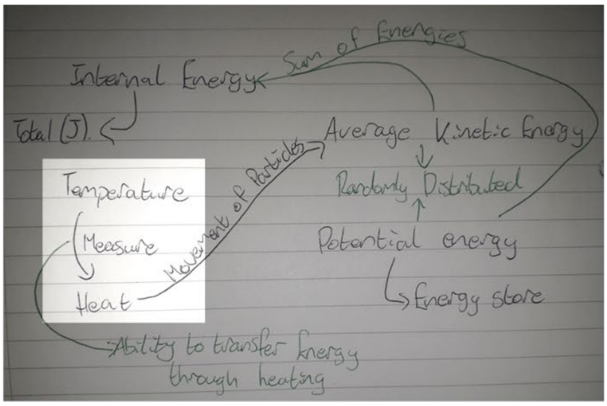
Qualitative comments from exit tickets and the focus group discussion do suggest that students attributed some learning value to concept mapping. However, the lack of a control group means any benefit from the intervention activities, over a similar lesson sequence without these, cannot be determined. As such, the conceptual understanding test scores cannot prove nor disprove that the teaching of metacognitive strategies directly boosted students' understanding. Nevertheless, in the focus group, students described how concept mapping supported them to spot their own knowledge gaps:

> *"The concept map… made it very clear which questions you wanted to ask [the teacher], or which words you needed a definition on." (S4)*

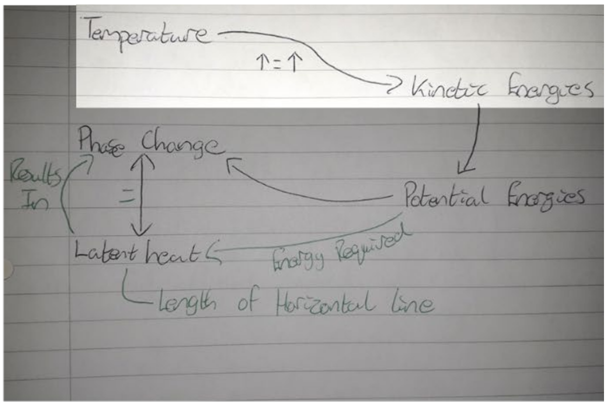
They further suggested that, for the purpose of increasing awareness of one's own understanding, the mapping activity was potentially more effective than simply attempting a series of recall questions:

> *"The concept map also made it very clear which questions you wanted to ask... If you just gave us one question, then it wouldn't highlight those areas so effectively." (S2)*

This aligns with conclusions from Yuruk et al. (2009), who suggest that students engaging in metaconceptual processes may be more likely to "recognize the phenomenon that they do not know or understand… possibly enhance[ing] students' motivation to learn the unknown or not understood conceptual entities" (p.472). This, furthermore, aligns with the rationale behind self-assessment, itself described as "an essential component of cognitive and constructivist theories of learning and motivation" (McMillan & Hearn, 2008, p.42). Additionally, the lesson sequence's regular use of the concept mapping activity – with students submitting their work each lesson – offered a source of formative assessment data regarding student misconceptions (see Figure 4) – a finding consistent with previous assessments of concept mapping as an in-class activity (see the discussion of 'quick concept-mapping', EEF, 2020).



Lesson 1 concept map
Student's map asserts that temperature is a 'measure' of heat, suggesting the presence of a common misconception.



Lesson 4 concept map
Map proposes that a substance's temperature increases in line with its particles' kinetic energies, suggesting the student's understanding has moved closer to the scientifically-accepted view.

Figure 4: Example of student S5's concept maps providing formative assessment information across the lesson sequence

In contrast, students' reflections were more mixed on the benefits to conceptual learning offered by the planning and evaluation activity. Students remarked that they were reticent to write out plans or evaluate them, with their submitted work similarly showing that completion of this was rare (see Table 6). Hence, with students rarely engaging with this activity as envisaged, our ability to evaluate its impact on learning is limited. Despite this, comments from the focus group offer some insight. One student (S3) reported the problem-solving planning and evaluation activity to be of limited benefit to their learning, suggesting that this may have stemmed from the accompanying problem-solving questions being somewhat repetitive or lacking challenge, resulting in the writing of plans and evaluations feeling "time-consuming". In contrast, they found that evaluating their plan was more useful for a longer and more complex 'Fermi problem', describing that "it helped me to see where I went wrong when we reviewed it all together" (S3). They concluded that the planning and evaluation activity may be more helpful "with mechanics… because the questions are much more complex" (S3) – a suggestion supported by Leonard et al.'s (1996) conclusion that "problems that are simple applications of… procedures are not optimal to assign as strategy-writing problems" (p.1502).

As noted by Yuruk et al. (2009), signs of positive impacts on awareness of concept learning does not constitute proof, nor a cause, of students actually mastering those concepts. This caveat is well-illustrated by comparing two students: S3 and S4. Reviewing their engagement in the metacognitive intervention activities, student S4 appears to be one of the class's more enthusiastic members –

reporting the exercises as either “quite helpful”/“very helpful” in every exit ticket and responding positively in the focus group, as well as being in the minority by reflecting positively on the act of writing their planned problem-solving approach. In contrast, student S3 displayed less enthusiasm, giving the activities the lowest average exit-ticket ratings in the class (for their ability to support consolidation of concepts), commenting that they found the planning and evaluation exercise to be “time-consuming”, and writing only very brief reflections. However, results from the conceptual understanding test did not correlate at all with this trend in enthusiasm or perceived engagement – with student S3 achieving the class’s highest score. Such a comparison serves as a reminder that, whilst potentially supportive, metacognitive strategies only play a part in the phenomenon of conceptual change, of which “the nature of the mechanisms… has not yet been adequately investigated” (Yuruk et al., 2009, p.472).

In summary, qualitative student feedback suggests that the concept mapping activity may have encouraged students to monitor their understanding of thermal physics concepts and to link new ideas with existing knowledge – processes that have both been linked with constructivist principles of learning. However, this study is unable to offer any direct proof of these metacognitive strategies driving improvements in students’ conceptual understanding.

Limitations of the study

As is common for action-research (Denscombe, 2017), this study’s findings are likely to be highly context-dependent, with the small sample size – six male Physics students from one Year 12 class – meaning that conclusions may not be generalised further. In particular, different results may have been found with younger students or with a different gender-balance, especially given that metacognition is widely-accepted to develop with age, and given reports that teenage female students’ metacognitive skills are typically advanced relative to those of their male counterparts (Veenman, Hesselink, Sleeuwaegen, Liem & Haaren, 2014). Furthermore, the study is limited by methodological challenges, with the lack of a control group preventing direct inference of the impact on conceptual understanding, and from the difficulties in assessing students’ metacognitive skills – arising from metacognition’s implicit, internal nature (Akturk & Sahin, 2011). Finally, as noted above, the study’s short duration resulted in students receiving significantly less exposure to the metacognitive activities than in comparable studies. Consequently, any ‘null’ results within this project (e.g., the ‘planning and evaluation’ activity yielding limited benefit) do not necessarily indicate that a metacognitive activity itself is intrinsically ineffective, since the result could instead stem from poor implementation.

Conclusion and implications

This study provides some (limited) backing for the claim that metacognitive strategies can support students' thermal physics learning. Variability was observed in students' implementation of the chosen strategies – namely, concept mapping and subsequent reflection, and the planning and evaluation of problem solving – with some expressing reticence to engage with writing and reflection activities, echoing previous findings (Leonard et al., 1996). Despite this, survey data suggests a subtle positive impact on students' perceived use of metacognitive skills linked to the chosen activities – specifically, those of planning and of linking concepts with previous knowledge and experiences. Qualitative data supports these findings, particularly indicating that concept mapping may have supported students to monitor and evaluate their own knowledge. However, as acknowledged in previous research (Yuruk et al., 2009), these findings do not amount to proof that these metacognitive strategies led directly to improvements in conceptual understanding.

Implications for practice

The principal finding from this study concerns the potential benefits of using concept mapping within physics topics that feature multiple closely linked concepts. Students identified that this activity supported them to monitor and assess the state of their own conceptual understanding – aligning with findings from previous research (Yuruk et al., 2009) – whilst also judging it to be more effective than the use of recall quizzing. Alongside these benefits for students' self-assessment and monitoring of learning, I would suggest that such an activity can form a useful formative assessment tool – with previous reports noting how concept mapping enables teachers to address misconceptions in real time (EEF, 2020)

Regarding improvements upon this study's brief intervention, I would recommend that future programmes aiming to teach and embed these metacognitive strategies do so over a more prolonged period. Finally, consistent with the recommendations of Veenman & Beishuizen (2004) and Zepeda et al. (2015), the introduction of these strategies would perhaps benefit from explicit scaffolding and support for students, enabling continued practice of the related skills.

Implications for research

There are various improvements that could facilitate a more thorough examination of this study's research questions. There is reason to believe that the project's short duration may have limited students' opportunity to gain confidence and competence in the metacognitive activities and associated skills. Therefore, a longer-term intervention, with more training sessions, may result in greater impacts (Dignath & Büttner, 2008). Relatedly, challenges were encountered when assessing students' metacognitive skills. Future studies may benefit from triangulating findings from students' self-reports with a broader range of indicators, particularly on-line measures such as 'think-aloud protocols', which allow simultaneous assessment of metacognitive activity (Ohtani & Hisasaka, 2018).

Finally, this project also suggests several additional research questions. This includes exploring whether the teaching of metacognitive strategies offers benefits to younger age groups and when learning other physics topics – or whether certain students or topics are particularly conducive to metacognition-related support. Additionally, future studies could explore whether these teaching practices influence students' views on the nature of science – given that the students here appear to have been encouraged to link science concepts to previous knowledge and experiences, and given how previous studies have recognised that tools such as concept mapping may support improved understanding of a discipline's hierarchical organisation (Romance & Vitale, 1999).

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Appendix 1

Metacognition Survey

The pre-project and post-project metacognition questionnaire, based upon the SEMLI-S (G. Thomas et al., 2008), is displayed in Table A, with full results given in Table B. The following guidance was given to students:

> *"This questionnaire asks you to describe HOW OFTEN you do each of the following practices when you learn Physics. There are no right or wrong answers. This is not a test and your answers will not affect any assessments. Your opinion is what is wanted. Your answers will help to improve future lessons. Your answers to this questionnaire will be saved in a password-protected electronic format. If used for any publications or presentations, all results will be anonymised completely and your responses will remain confidential."*

#	Statement	Subscale of SEMLI-S	Response scale				
			1. Never / rarely	2. Sometimes	3. Half of the time	4. Frequently	5. Always / almost always
1	I seek to connect what I learn from what happens in Physics lessons with out-of-class science activities (e.g. field trips, science visits, documentaries).	Constructivist connectivity					
2	I adjust my plan for a learning task if I am not making the progress I think I should.	Monitoring, evaluation and planning					
3	I seek to connect what I learn from out-of-class science activities with what happens in Physics lessons.	Constructivist connectivity					
4	I plan to check my progress during a learning task.	Monitoring, evaluation and planning					
5	I try to understand clearly the aim of a task before I begin it.	Monitoring, evaluation and planning					
6	I evaluate my learning processes with the aim of improving them.	Monitoring, evaluation and planning					
7	I seek to connect what I learn in my life outside of class with ideas in my Physics lessons.	Constructivist connectivity					
8	I consider what type of thinking is best to use before I begin a learning task.	Monitoring, evaluation and planning					
9	I seek to connect the information in Physics lessons with what I already know.	Constructivist connectivity					
10	I consider whether or not a plan is necessary for a learning task before I begin that task.	Monitoring, evaluation and planning					
11	I seek to connect what I learn from out-of-class science activities (e.g. field trips or science museum visits) with what happens in Physics lessons.	Constructivist connectivity					
12	I stop from time to time to check my progress on a learning task.	Monitoring, evaluation and planning					
13	I try to predict possible problems that might occur with my learning.	Monitoring, evaluation and planning					
14	I seek to connect what I learn from what happens in the Physics classroom with out-of-class science activities.	Constructivist connectivity					
15	I assess how much I am learning during a learning task.	Monitoring, evaluation and planning					
16	I seek to connect what I learn in other subject areas with Physics.	Constructivist connectivity					

Table A: Metacognition survey statements used in pre-project and post-project student questionnaires

Table A includes an indication of which subscale of the SEMLI-S that each question originated from – either the "Constructivist connectivity" subscale or "Monitoring, evaluation and planning" subscale.

Full results of the pre- and post-project surveys are shown in Table B. Note, to enable a direct comparison, the results in this table only compare the responses of the five students who took both the pre-project and post-project surveys; the responses of the sixth individual, who did not submit a pre-project survey, have been excluded.

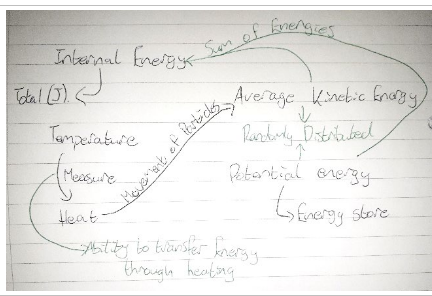
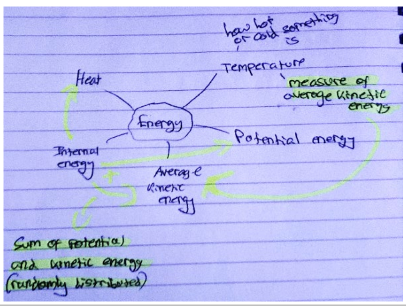
#	Statement	Average score (original scale of 1-5)			% of responses ≥ 4+ (original scale of 1-5)		
		Pre-	**Post-**	**Change**	**Pre-**	**Post-**	**Change**
1	I seek to connect what I learn from what happens in Physics lessons with out-of-class science activities (e.g., field trips, science visits, documentaries).	3.2	3.4	+0.2	60%	60%	0%
2	I adjust my plan for a learning task if I am not making the progress I think I should.	3.2	3.6	+0.4	60%	60%	0%
3	I seek to connect what I learn from out-of-class science activities with what happens in Physics lessons.	3.0	3.2	+0.2	20%	40%	+20%
4	I plan to check my progress during a learning task.	3.4	2.6	-0.8	40%	40%	0%
5	I try to understand clearly the aim of a task before I begin it.	4.4	4.4	0.0	100%	100%	0%
6	I evaluate my learning processes with the aim of improving them.	3.2	3.4	+0.2	40%	40%	0%
7	I seek to connect what I learn in my life outside of class with ideas in my Physics lessons.	3.0	3.8	+0.8	20%	80%	+60%
8	I consider what type of thinking is best to use before I begin a learning task.	3.2	3.2	0.0	40%	40%	0%
9	I seek to connect the information in Physics lessons with what I already know.	4.6	4.6	0.0	100%	100%	0%
10	I consider whether or not a plan is necessary for a learning task before I begin that task.	2.2	3.2	+1.0	0%	60%	+60%
11	I seek to connect what I learn from out-of-class science activities (e.g., field trips or science museum visits) with what happens in Physics lessons.	3.0	3.0	0.0	20%	40%	+20%
12	I stop from time to time to check my progress on a learning task.	2.8	2.8	0.0	20%	40%	+20%
13	I try to predict possible problems that might occur with my learning.	3.4	3.4	0.0	60%	40%	-20%
14	I seek to connect what I learn from what happens in the Physics classroom with out-of-class science activities.	2.8	3.0	+0.2	40%	40%	0%
15	I assess how much I am learning during a learning task.	4.0	2.8	-1.2	60%	20%	-40%
16	I seek to connect what I learn in other subject areas with Physics.	3.8	4.2	+0.4	60%	100%	+40%

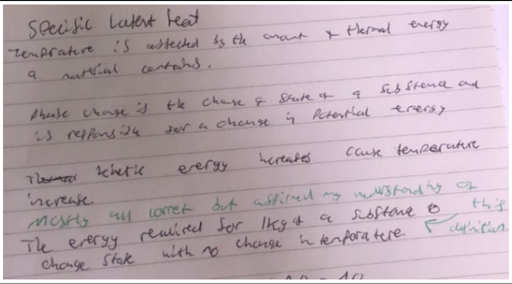
Table B: Full results of the pre-project and post-project metacognition survey

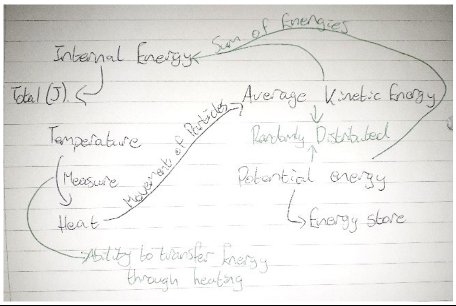
Appendix 2

Categorisation of student work

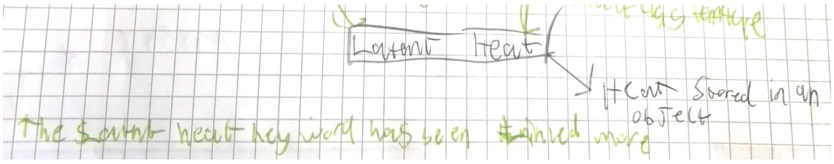
As part of the analysis of submitted work from the intervention activities, students' concept maps and written problem-solving were reviewed and categorised into approximate descriptive groups, according to the style of completion. The frequency of examples in each group was counted and summarised in Table 6 in the main text. This appendix aims to provide insight into this categorisation process, offering examples against each of the categories (showing both examples of work that met the criteria, and examples of ways in which work differed from these desired formats). Table C adopts a similar structure as is used in Table 6, providing examples and – where appropriate – descriptions of each of these.

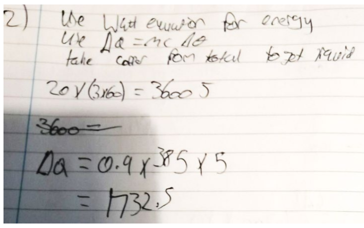
<table>
<tr><th>Criteria for classification of work</th><th>Example(s)</th></tr>
<tr><td colspan="2">Concept mapping and reflection</td></tr>
<tr><td>✓ Prompted words included in map with nodes and <u>labelled</u> links</td><td>(Includes all work that fits into the subcategories A, B, C below)</td></tr>
<tr><td>A. Criterion met: Prompted words included in map with nodes and <u>labelled</u> links</td><td>
</td></tr>
<tr><td>B. Criterion not met: Typical 'mind-map' structure with <u>unlabelled</u> links</td><td>This category is defined by a map's lack of labelled links, and its structure – with all nodes emanating from one central concept. Such a structure would be familiar for students creating a mind-map for one overarching revision topic. The concept mapping approach advocated in this study avoided enforcing such a hierarchical relationship onto students' thinking (as I wanted to encourage students to articulate how they truly viewed the relationships between topics). It is therefore worth noting that the central concept adopted in the example below, "Energy", was not included in as a concept mapping prompt word, but was instead introduced by the student themselves.

</td></tr>
</table>

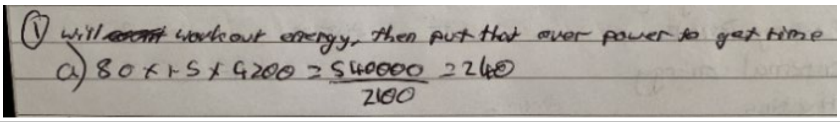
<table>
<tr><th>Criteria for classification of work</th><th>Example(s)</th></tr>
<tr><td>C. Criterion not met: List of written definitions / sentences only</td><td>

</td></tr>
<tr><td>✓ Map updated at end of lesson</td><td>Students were asked to update their maps in a different colour pen / pencil. Any maps with additions in another colour were coded in this category.



</td></tr>
<tr><td>✓ Written reflective comments</td><td>Any examples where students wrote an evaluative comment onto their concept map. For example, the below example includes an evaluative comment (in green): “The latent heat key word has been linked more”.


</td></tr>
<tr><td colspan="2">Problem solving planning and evaluation</td></tr>
<tr><td>✓ Initial written plans include algorithmic steps</td><td>This category was defined as work that included brief written descriptions of the simple computational steps students would take to answer a question. For example, these plans often identified the equations that the student was intending to use, and which final quantities they were aiming to calculate.




</td></tr>
<tr><td>✓ Initial written plans reference broader conceptual understanding</td><td>Such a category would have included plans that made reference to the conceptual principles being applied (e.g., “apply principle of conservation of energy to work out energy transfer by heating”). However, no plans of this description were seen in the small number of examples reviewed.</td></tr>
<tr><td>✓ Work includes an evaluative comment reflecting on conceptual understanding</td><td>Students were asked to include evaluative comments reflecting on their problem-solving plans and subsequent attempts. As with the concept map, students were asked to write this in a different colour to their initial plan and written solutions. Examples of evaluative comments include those in the subcategories A and B below.</td></tr>
</table>

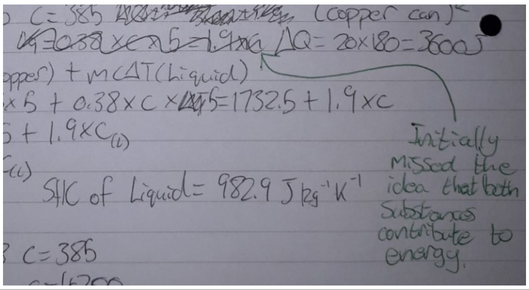
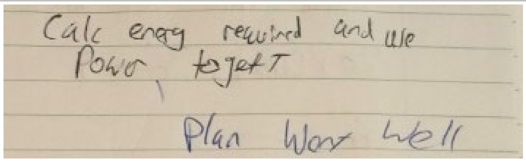
Criteria for classification of work	Example(s)
A. **Criterion met:** Evaluations that include one or more comments relating to conceptual understanding	Whilst no initial *plans* I reviewed included reference to qualitative, conceptual principles, two students' evaluative comments did provide some evidence of subsequent conceptual reflection. For example, the comment in green below references the student's reflections related to the principle of conservation of energy in the context of a 'methods of mixtures' specific heat capacity question. 
B. **Criterion not met:** Comments restricted to basic judgement of problem-solving steps	

Table C: Examples of student's work against each category as used in Table 6 (main text)

Appendix 3

Example exit ticket

Figure A shows an example of the exit tickets used to collect data and to encourage student self-reflection at the end of lessons in the study. This example is taken from lesson 1: "Internal energy & energy transfer", administered via the school's Microsoft Forms platform. Exit tickets in subsequent lessons followed the same format, with the focus of the conceptual questions being adjusted to match the lesson topic, and the focus of questions three and four being adjusted in accordance with the metacognitive interventions deployed in that lesson.

Y12 Physics Exit Ticket - 05/03/2021

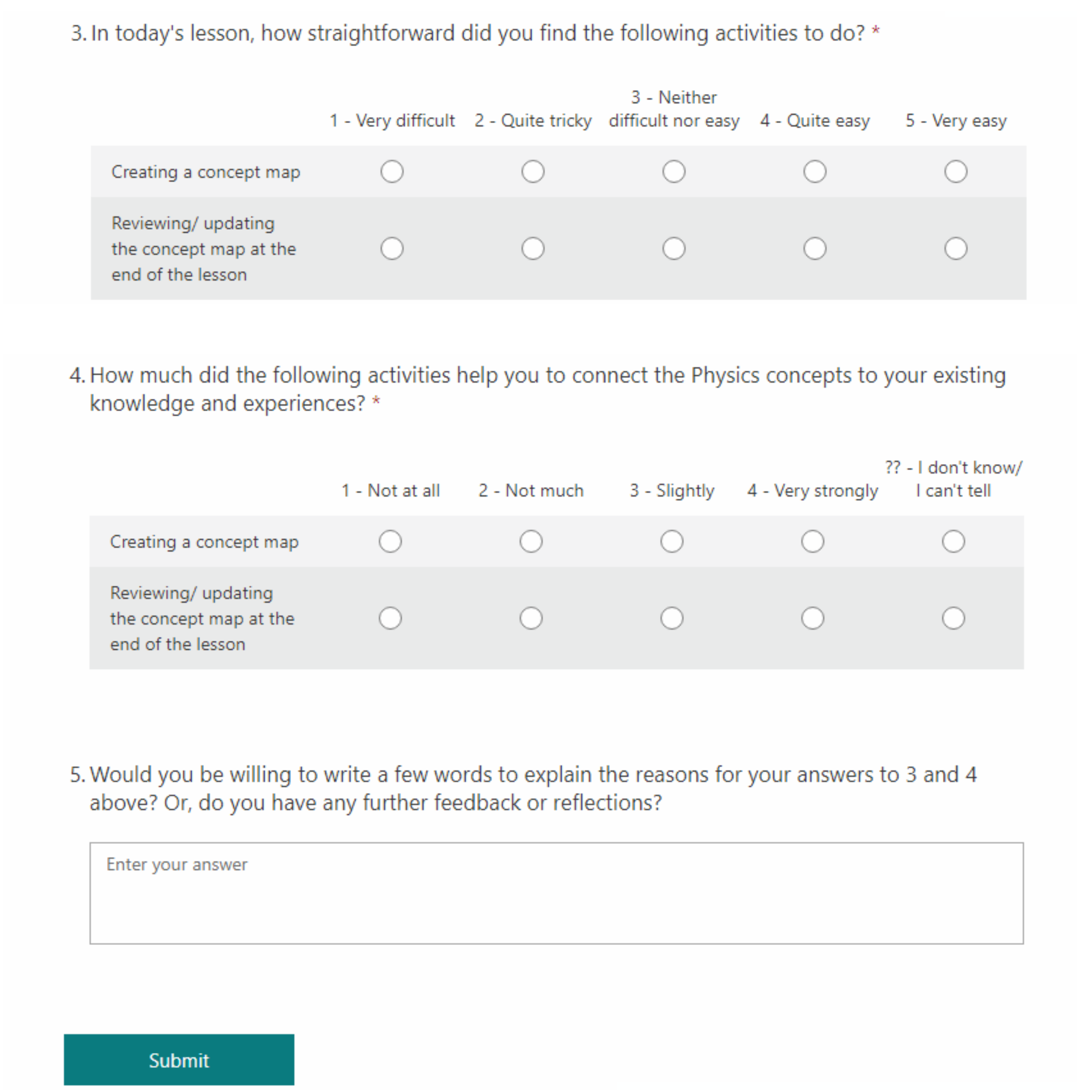
* Required

1. What is heat? *

- a) The amount of thermal energy in an object
- b) The energy that moves from a hotter object to a colder object
- c) An invisible fluid-like substance that flows from a hotter object to a colder object
- d) both a and b
- e) both a and c
- f) both b and c

2. How will the temperature of a substance change if we increase the potential energy of the interactions between the particles but leave the particles' motion unchanged? *

- Temperature will increase
- Temperature will decrease
- Temperature will not change
- We would need more information to answer this



3. In today's lesson, how straightforward did you find the following activities to do? *

	1 - Very difficult	2 - Quite tricky	3 - Neither difficult nor easy	4 - Quite easy	5 - Very easy
Creating a concept map	○	○	○	○	○
Reviewing/ updating the concept map at the end of the lesson	○	○	○	○	○

4. How much did the following activities help you to connect the Physics concepts to your existing knowledge and experiences? *

	1 - Not at all	2 - Not much	3 - Slightly	4 - Very strongly	?? - I don't know/ I can't tell
Creating a concept map	○	○	○	○	○
Reviewing/ updating the concept map at the end of the lesson	○	○	○	○	○

5. Would you be willing to write a few words to explain the reasons for your answers to 3 and 4 above? Or, do you have any further feedback or reflections?

Enter your answer

Submit

Figure A: Example Microsoft Forms exit ticket survey,
used at the end of lesson 1 on 'Internal energy and energy transfer'

Appendix 4

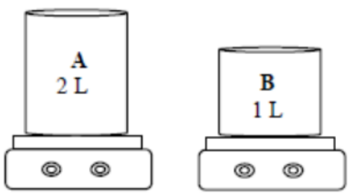
Conceptual understanding test

Table D below gives an overview of the questions used in the end-of-project conceptual survey, as well as an attribution as to each question's original source. Questions were derived from three sources:

1. Thermal Concept Evaluation, TCE (Yeo & Zadnik, 2001).

2. Thermodynamic Concept Survey, TCS (Wattanakasiwich et al., 2013). It should be noted that a number of questions in this survey were originally sourced from the TCE (Yeo & Zadnik, 2001). Where this is the case, the question has been attributed to the TCE, but with a note made to acknowledge its use in both instruments.

3. New questions written by the author for this study (questions 4, 5, 10 and 12). Questions 4, 5 and 12 were introduced based upon common misconceptions of internal energy that emerged from the lesson sequence and in students' responses to exit ticket conceptual questions. These questions assess students' understanding of internal energy, they include distractors that relate to an incorrect understanding of the relationship between a substance's temperature and its particles' kinetic energies, and between a substance's state of matter and its particles' potential energies. Question 10 assesses students' understanding of specific heat capacity and continuous flow heating set-ups, testing to see if students incorrectly assume that an increased fluid flow rate will lead to a greater change in temperature.

#	Question	Question source	Multi-choice answer options (correct response indicated by a ✓ symbol)				
1	Cup A contains 100 grams of water at 0°C but cup B contains 200 grams of water at 50°C. The contents of the two cups are mixed together in an insulated container (no heat transfer occurs). When it reaches thermal equilibrium, what is the final temperature of the water in the container?	TCS	Between 0°C and 25°C	25°C	✓ Between 25°C and 50°C	50°C	Higher than 50°C
2	100 grams of ice at 0°C and 100 grams of water at 0°C are put into a freezer, which has a temperature below 0°C. After waiting until their temperature equals to the freezer temperature, which one will eventually lose the greatest amount of heat?	TCE (later adopted in TCS)	The 100 grams of ice.	✓ The 100 grams of water.	They both lose the same amount of heat because their initial temperatures are the same.	There is no answer because ice does not contain any heat.	There is no answer because you cannot get water at a temperature of 0°C.
3	Cup A contains 100 grams of water and cup B contains twice as much water. The water in both cups was initially at room temperature. Then the water in cup A was heated to 75°C and the water in cup B was heated to 50°C. When the water in both cups cooled down to room temperature, which cup had more heat transferred from it? 	TCS	Cup A had more heat transferred out.	Cup B had more heat transferred out.	✓ Both cups had the same amount of heat transferred.	Not enough information is given to determine the answer.	
4	How will the temperature of a substance change if we increase the potential energy of the interactions between the particles but leave the particles' motions unchanged?	Written by author of this study	Temperature will increase	Temperature will decrease	✓ Temperature will not change	We need more information	
5	Beaker A and beaker B each contain different volumes of different liquids. Both liquids are at the same temperature. Which of the following statements are true?	Written by author of this study	The liquids in both containers have the same internal energy	The particles in both containers have the same average speed	✓ The particles in both containers have the same average kinetic energies	The liquids in both containers have the same average heat	The particles in both containers have the same average potential energies
6	Cup A contains 2 litres of water and cup B contains 1 litre of water. The water in both cups was initially at room temperature. Then both cups are placed on a hot plate and heated until the water in the cup is boiling (100°C). Which statement is correct? 	TCS	Water in both cups has the same heat transfer.	✓ Water in cup A has more heat transfer.	Water in cup B has more heat transfer.		

#	Question	Question source	Multi-choice answer options (correct response indicated by a ✓ symbol)				
7	After cooking some eggs in boiling water, the eggs are cooled by putting them into a bowl of cold water. Which of the following explains the cooling process?	TCE (later adopted in TCS)	Temperature is transferred from the eggs to the water.	Cold moves from the water into the eggs.	Hot objects naturally cool down.	✓ Energy is transferred from the eggs to the water.	
8	Amy took two glass bottles containing water at 20°C and wrapped them in washcloths. One of the washcloths was wet and the other was dry. 20 minutes later, she measured the water temperature in each. The water in the bottle with the wet washcloth was 18°C, the water in the bottle with the dry washcloth was 22°C. The most likely room temperature during this experiment was:	TCE	✓ 26°C	21°C	20°C	18°C	
9	Select the best answer that completes this sentence: *"Sweating cools you down because the sweat lying on your skin..."*	TCE	...wets the surface, and wet surfaces draw more heat out than dry surfaces.	...drains heat from the pores and spreads it out over the surface of the skin.	...is the same temperature as your skin but is evaporating and so is carrying heat away.	✓ ...is slightly cooler than your skin because of evaporation and so heat is transferred from your skin to the sweat.	
10	Water flowing out of a heating unit is at a temperature that is ΔT greater than the water flowing into the unit. Two changes are then made: 1. The water is replaced with another liquid with half the specific heat capacity. 2. The mass flow rate of liquid is tripled. What will the temperature difference now be between the liquid flowing out of the unit vs the liquid flowing in?	Written by author of this study	(1/6) × ΔT	(1/3) × ΔT	✓ (2/3) × ΔT	(3/2) × ΔT	3 × ΔT
11	Four students were discussing things they did as kids. The following conversation was heard: Ami: "I used to wrap my dolls in blankets but could never understand why they didn't warm up."	TCE	Nick replied: "It's because the blankets you used were probably poor insulators.	Lyn replied: "It's because the blankets you used were probably poor conductors.	Jay replied: "It's because the dolls were made of material which did not hold heat well."	Kev replied: "It's because the dolls were made of material which took a long time to warm up."	✓ Joy replied: "You're all wrong."
12	Water in a pan on a stove is boiling to form water vapour. During this change, the temperature of the liquid and vapour is staying constant at the boiling point (100°C). Which of the following is true?	Written by author of this study	The particles in the vapour are, on average, moving faster than those in the liquid	The particles in the vapour have, on average, a lower potential energy than those in the liquid	The particles in the vapour have, on average, a lower kinetic energy than those in the liquid	✓ None of the above are true	

Table D: Multiple-choice questions adopted in end-of-project conceptual understanding test

As with the metacognition survey and exit tickets, this was delivered via an online Microsoft Forms survey