

Cognitive Science in the Science Classroom

What it gets right, where it has been stretched too far, and what science teachers should do with it

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In little more than a decade, cognitive science has gone from a niche interest to the dominant language of teaching in England. Retrieval quizzes, worked examples and talk of "cognitive load" are now everyday features of science lessons. This article asks what the evidence actually supports, why science is a special case, and where good ideas have turned into rituals that no longer serve learning.

The cognitive science moment

Walk into almost any secondary science department in England and you will find cognitive science at work. Lessons begin with a retrieval quiz. Teachers model calculations step by step before pupils try them. Schemes of work are planned with spaced revisits to earlier topics. Training days cite Rosenshine's "Principles of Instruction" (Rosenhine, 2012) and Sweller's cognitive load theory (Sweller, 1988). When the Education Endowment Foundation (EEF) surveyed teachers for its 2021 review of the evidence, more than 85% reported using approaches inspired by cognitive science (Perry et al., 2021).

Much of this is to the good. Cognitive science offers something that education has often lacked: a reasonably well-tested account of how human memory works, and a set of practical approaches that follow from it. The EEF's guidance on secondary science includes "supporting pupils' memory skills for retention and retrieval" among its seven recommendations (Education Endowment Foundation, 2018). For a subject as content-heavy as GCSE science, ideas that help pupils remember what they have been taught are welcome.

But the EEF review that recorded this enthusiasm also carried a warning. Its authors concluded that principles from cognitive science are "neither myths to be discounted, nor silver bullets", and that findings from the laboratory "do not always translate into effective teaching and learning in the classroom" (Perry et al., 2021). The review found that much of the evidence for popular approaches came from controlled studies with university students, not from teachers working with their own classes. For retrieval practice, perhaps the most widely adopted approach, one analysis of the review noted that only one of the 21 studies it drew on was delivered by a regular class teacher (Runeckles, 2021).

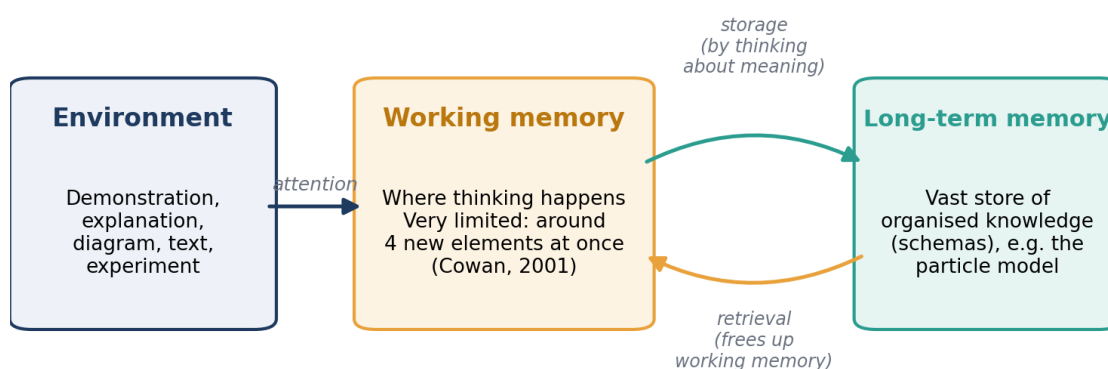
The argument of this article is that science teachers should take cognitive science seriously, but use it as a set of principles to think with rather than a checklist to comply with. Science has particular features that make cognitive science especially relevant: abstract ideas, heavy mathematical demands, several levels of representation and stubborn misconceptions. The same features also mean that some popular applications fit science poorly. The sections that follow set out the core

model, explain why science puts unusual strain on pupils' memory, examine the main approaches and their evidence, and identify where they have been stretched too far.

A simple model of the mind

Most applications of cognitive science in schools rest on a simple model of memory (Figure 1). Information from the environment, such as a teacher's explanation, a diagram or an experiment, enters **working memory** if we pay attention to it. Working memory is where conscious thinking happens, and it is severely limited. Estimates vary, but a widely cited review suggests that adults can hold around four new "chunks" of information at once (Cowan, 2001). Information that is not rehearsed or connected to something meaningful is quickly lost.

A simple model of memory (after Willingham, 2009)



Learning is a change in long-term memory. Knowledge already held there makes new thinking easier, because it can be retrieved as one 'chunk' instead of many separate elements.

Figure 1. A simple model of memory, after Willingham (2009). Working memory is small; long-term memory is vast. Knowledge stored in long-term memory can be retrieved as a single chunk, which frees working memory for new thinking.

Long-term memory, by contrast, is vast and durable. Knowledge there is organised into **schemas**: connected structures of ideas that can be retrieved and used as a single unit. An experienced physics teacher who reads "a ball is dropped from 20 m" immediately activates a schema that links gravitational potential energy, kinetic energy, conservation of energy and the relevant equations. A pupil meeting the topic for the first time must hold each of these ideas separately in working memory, if they have them at all.

Willingham (2009) summarises the implication memorably: memory is the residue of thought. Pupils remember what they think about. Learning, in this model, is a change in long-term memory, and the purpose of teaching is to help pupils build well-organised schemas that they can later retrieve with little effort.

Cognitive load theory builds on this model (Sweller, 1988; Sweller, van Merriënboer and Paas, 2019). It distinguishes two main sources of load on working memory. **Intrinsic load** comes from the material itself, in particular how many elements must be handled at once and how much they interact. **Extraneous load** comes from the way the material is presented: a cluttered slide, a diagram whose labels are separated from the parts they describe, or a task that asks pupils to search for a method rather than learn one. Good instruction manages intrinsic load by sequencing

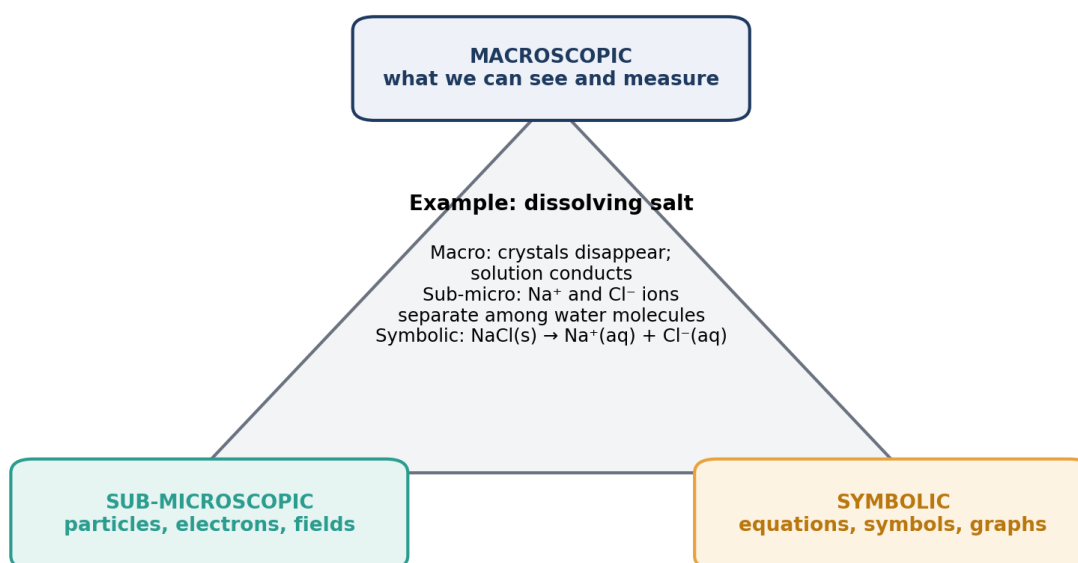
and building prior knowledge, and minimises extraneous load so that working memory is free for the thinking that leads to learning.

Why science is especially hard on working memory

Science is not just another subject to which these ideas apply. Several features of science make it particularly demanding on working memory, which helps explain why cognitive science has been taken up so enthusiastically by science teachers.

Science operates on several levels at once. Johnstone (1991) argued that much of the difficulty of chemistry comes from its three levels of representation: the **macroscopic** (what we can see and measure), the **sub-microscopic** (particles, ions and electrons) and the **symbolic** (formulae, equations and diagrams). Experts move between these levels without effort. Novices are often asked to handle all three at once, for example watching salt dissolve, imagining ions separating among water molecules and writing an ionic equation, all in the same few minutes (Figure 2). The same applies in physics. In a lesson on electric current, pupils must connect an ammeter reading (macroscopic), a model of drifting charge carriers (sub-microscopic) and the equation $Q = It$ with its circuit symbols (symbolic).

Johnstone's triangle: three levels of thinking in science



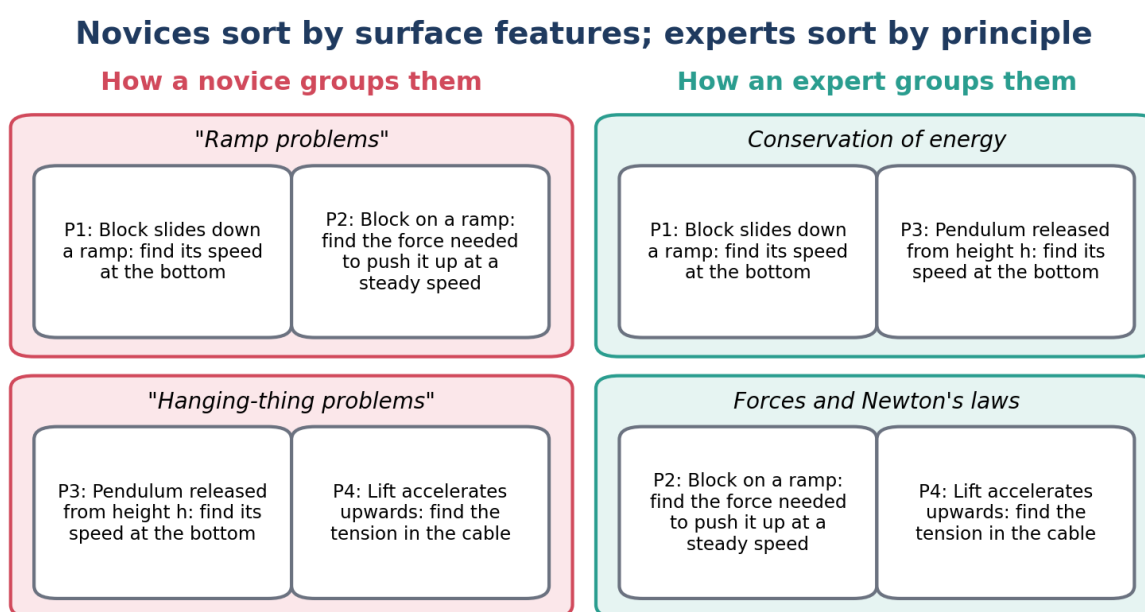
Experts move between all three levels easily. Novices are often asked to handle all three at once, overloading working memory.

Figure 2. Johnstone's triangle. Science asks pupils to think at three levels at once; experts move between them easily, but for novices each level adds to the load on working memory. Based on Johnstone (1991).

Science has high element interactivity. Some material can be learned one element at a time: the symbol for sodium, the unit of power. But understanding why a heavier trolley does not reach the bottom of a frictionless ramp any faster requires holding several interacting ideas together: gravitational potential energy, kinetic energy, mass cancelling in the equation, and the idea that both depend on mass in the same way. Sweller et al. (2019) describe material like this as having high element interactivity. It is intrinsically demanding, and it is exactly the kind of material that science is full of.

Science depends on mathematics. Many GCSE physics and chemistry questions require pupils to select an equation, rearrange it, convert units and calculate, all while keeping track of the physical situation. If any of these steps is not secure in long-term memory, it consumes working memory that is needed for the science. A pupil who has to think hard about how to rearrange $V = IR$ has less capacity left to think about what the answer means.

Experts and novices see different problems. One of the most influential studies in the field showed that physics experts and novices categorise problems differently (Chi, Feltovich and Glaser, 1981). Novices grouped problems by surface features, such as "problems with inclined planes". Experts grouped them by the underlying principle, such as conservation of energy or Newton's second law (Figure 3). The experts' long-term memory held schemas organised around principles, which allowed them to recognise what kind of problem they faced. Novices, lacking those schemas, were drawn to what was visible.



Illustrative problems based on the pattern reported by Chi, Feltovich and Glaser (1981).

Figure 3. Novices and experts sort the same physics problems differently. Novices group problems by surface features; experts group them by the physical principle needed to solve them. Illustrative problems based on Chi, Feltovich and Glaser (1981).

This study matters for science teachers because it shows what expertise looks like and what teaching is trying to build. The aim is not simply that pupils remember facts, but that their knowledge becomes organised around the big ideas of science, so that they can recognise when those ideas apply.

Principle 1: Guide novices explicitly, then remove the guidance

The most contested claim associated with cognitive science is that novices learn more from explicit instruction than from minimally guided discovery. Kirschner, Sweller and Clark (2006) argued that asking novices to find out principles for themselves overloads working memory, because they must search for a solution while also trying to learn from it. Their paper became a reference point for a wider shift in English schools towards teacher-led explanation and modelling.

The strongest evidence behind this claim is the **worked example effect**. In a classic series of experiments, students who studied worked examples of algebra problems learned more, and solved later problems faster, than students who spent the same time solving the problems themselves (Sweller and Cooper, 1985). The explanation is that solving an unfamiliar problem uses working memory for searching rather than learning, whereas studying a worked example directs attention to the steps and their reasons.

For science teachers, worked examples are most obviously useful in calculations, but they apply more widely: to drawing ray diagrams, balancing equations, constructing a six-mark explanation or planning an investigation. The key is that pupils study the example actively, explaining to themselves why each step is taken, rather than copying it.

Worked examples are not meant to last for ever. Renkl and Atkinson (2003) showed the value of **fading**: gradually removing steps from worked examples so that pupils complete more of each problem themselves, until they are solving problems independently (Figure 4). In a GCSE physics lesson on kinetic energy, the teacher might show a complete worked example, then give a completion problem with the substitution done, then a faded example with only the equation provided, before pupils attempt problems on their own.

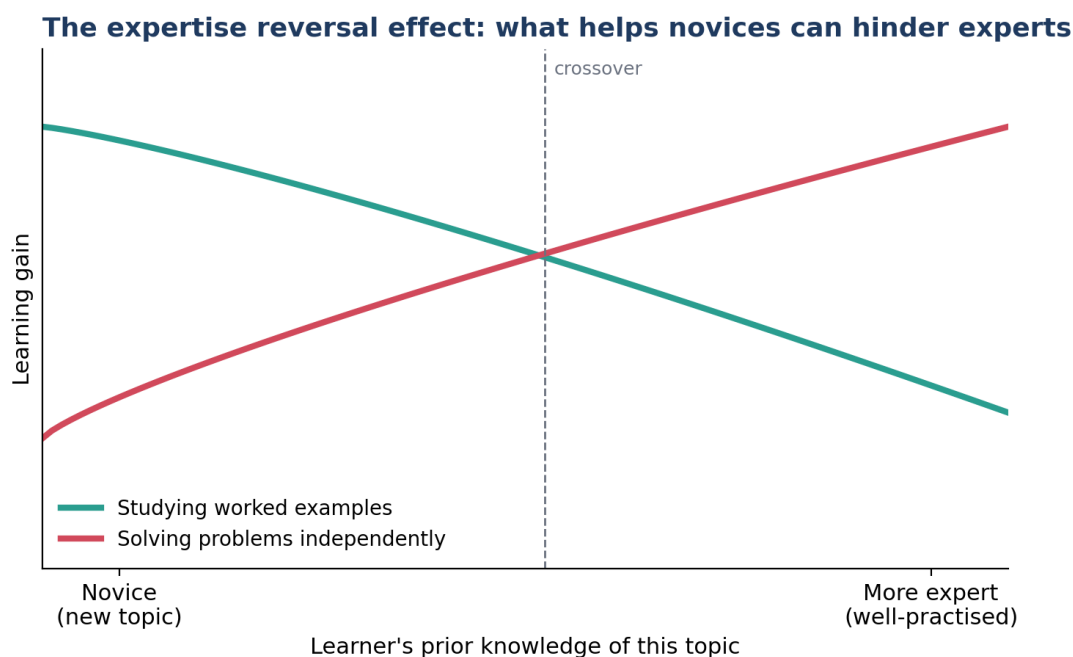
Fading a worked example: kinetic energy calculation

	1. Full worked example	2. Completion problem	3. Faded example	4. Independent problem
Write the equation	$KE = \frac{1}{2}mv^2$	$KE = \frac{1}{2}mv^2$	$KE = \frac{1}{2}mv^2$	_____
Substitute values	$KE = \frac{1}{2} \times 2.0 \times 3.0^2$	$KE = \frac{1}{2} \times 1.5 \times 4.0^2$	_____	_____
Calculate	$= \frac{1}{2} \times 2.0 \times 9.0 = 9.0$	= _____	_____	_____
Answer with unit	9.0 J	_____ J	_____	_____

Each step removes support as knowledge builds (after Renkl and Atkinson, 2003). Example values: m in kg, v in m/s.

Figure 4. Fading a worked example for a kinetic energy calculation. Support is removed one step at a time as pupils' knowledge builds. Based on the principle described by Renkl and Atkinson (2003).

Fading matters because of the **expertise reversal effect** (Kalyuga et al., 2003). Guidance that helps novices can become redundant, and even harmful, for learners who already know the material. A pupil who can already calculate kinetic energy fluently gains little from studying another full worked example; processing the redundant steps may even get in the way. As expertise grows, independent problem solving becomes the more effective activity (Figure 5).



Schematic illustration of the pattern described by Kalyuga et al. (2003); not plotted from a single dataset.

Figure 5. The expertise reversal effect. Worked examples help most when a topic is new; as pupils' knowledge grows, independent problem solving becomes more effective. Schematic illustration based on Kalyuga et al. (2003).

The expertise reversal effect is a useful corrective to the idea that cognitive science simply means "more teacher talk". It implies that guidance should be matched to what pupils already know, and that the same class may need different amounts of support for different topics. It also implies that in a mixed-attainment class, some pupils will be ready to work independently well before others.

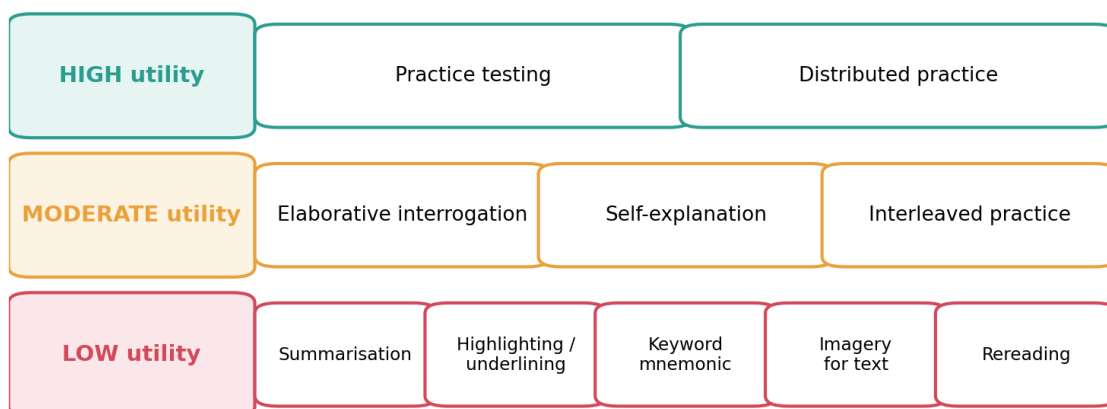
A related finding concerns how materials are designed. Chandler and Sweller (1991) showed that when learners have to mentally combine two separate sources of information, such as a diagram and a block of text that explains it, the effort of combining them adds extraneous load. This **split-attention effect** has direct implications for science resources. A circuit diagram with labels placed next to the components they describe is easier to learn from than the same diagram with a separate key. An annotated graph is easier than a graph and a paragraph on the facing page.

Principle 2: Make pupils retrieve what they have learned

If one approach has become synonymous with cognitive science in English schools, it is **retrieval practice**: asking pupils to recall information from memory, rather than re-reading or being told it again. The evidence for its benefits is among the strongest in educational psychology.

In a well-known laboratory study, students who read a prose passage and then practised recalling it remembered much more a week later than students who spent the same time re-reading it, even though the re-readers felt more confident (Roediger and Karpicke, 2006). The act of retrieval appears to strengthen memory and make it easier to access in future. Dunlosky et al. (2013), in a major review of ten common study techniques, rated practice testing as one of only two techniques of "high utility", alongside distributed practice (Figure 6). Techniques that pupils commonly use, such as re-reading and highlighting, were rated low.

How useful are common study techniques? (Dunlosky et al., 2013)



Ratings reflect how well each technique generalises across learners, materials and conditions, not just whether it ever works.

Figure 6. Utility ratings for ten common study techniques from Dunlosky et al. (2013). Ratings reflect how consistently each technique has been shown to work across learners, materials and conditions.

Crucially for teachers, retrieval practice has been tested in real classrooms, including science classrooms. McDaniel et al. (2011) found that low-stakes quizzes in a US middle school science class improved pupils' performance on later unit tests and end-of-semester exams. Agarwal, Nunes and Blunt (2021) systematically reviewed 50 classroom experiments involving more than 5,000 students and found that the majority of effects (57%) were medium or large. The benefits held across age groups, subjects and quiz formats.

Two caveats are worth noting. First, as the EEF review highlighted, very few studies involve ordinary teachers designing and running retrieval practice in their own lessons over long periods (Perry et al., 2021). Second, comparisons with other strategies are not always as clear-cut as they appear. Karpicke and Blunt (2011) reported that retrieval practice produced more learning from science texts than creating concept maps. However, a later replication found that the advantage disappeared when students who made concept maps were also given time to memorise the material, suggesting that part of the original difference came from the study design (Mayrhofer, Kuhbandner and Frischholz, 2023).

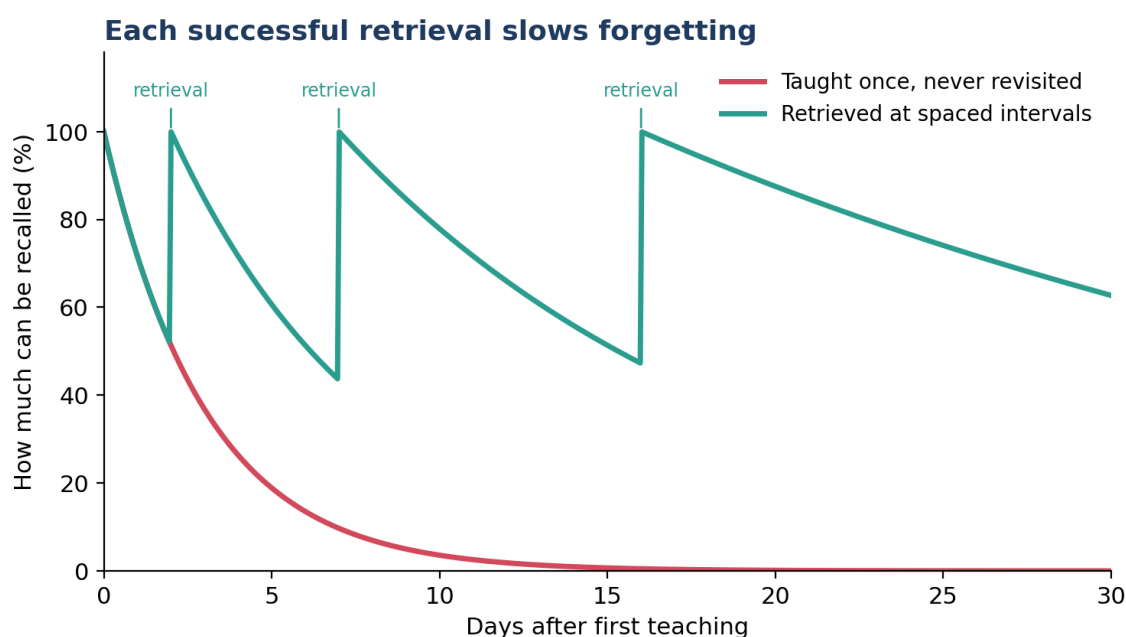
The more important question for science teachers is *what* pupils retrieve. A retrieval quiz that asks for isolated facts (the unit of resistance, the name of a cell organelle) will strengthen memory of isolated facts. But science requires connected understanding: why resistance increases with temperature in a filament lamp, or how the structure of the mitochondrion relates to its function. Retrieval practice can, and should, target these connections. Useful forms include:

- **Explain-the-link questions**, such as "Why does increasing temperature increase the rate of reaction?", rather than "What is activation energy?"
- **Brain dumps** on a topic, followed by comparison with a model or a concept map, which reveal gaps in how ideas connect.
- **Retrieving procedures**, such as rearranging an equation or describing a required practical method from memory.
- **Mixing old and new**, so that quizzes revisit topics from weeks or months earlier, not just last lesson.

Principle 3: Space it out and mix it up

The **spacing effect** is one of the oldest findings in psychology. Ebbinghaus (1885) showed that memory fades rapidly after learning, and that material revisited after a delay is retained much better than material studied in a single block. A large meta-analysis confirmed that spacing study across time improves long-term retention compared with massed study, and that the optimal gap grows with the length of time over which the material needs to be remembered (Cepeda et al., 2006).

Combined with retrieval practice, spacing produces a powerful effect: each successful retrieval after a delay slows the rate of later forgetting (Figure 7). For a GCSE course that lasts two or three years and ends in terminal examinations, the implication is clear. Topics taught in Year 10 will largely be forgotten by the summer of Year 11 unless they are revisited, and revisiting through retrieval is more effective than re-teaching.



Schematic illustration of the spacing and retrieval effects (Ebbinghaus, 1885; Cepeda et al., 2006); curves are not real data.

Figure 7. A schematic illustration of how spaced retrieval slows forgetting. Without revisiting, recall falls quickly; each well-timed retrieval resets and slows the decline. The curves are illustrative, not real data.

Bjork and Bjork (2011) describe spacing as a **desirable difficulty**: something that makes learning feel harder and slower in the short term but improves long-term retention. This creates a practical problem. Pupils, and sometimes teachers, judge learning by how fluent it feels in the moment, and spacing reduces that fluency. A class that has just practised twenty identical calculations will look as though it has learned well. A class whose practice is spaced and mixed will make more errors during the lesson but remember more later.

Interleaving, mixing different types of problem within a practice session rather than practising one type in a block, is closely related. In mathematics, Rohrer and Taylor (2007) found that students who practised mixed problems performed much better on a delayed test than those who practised in blocks, even though blocked practice looked better during the practice itself. A systematic review of interleaving in concept learning found benefits for both memory and transfer, with effects largest when the differences between categories were subtle. It also noted that most

studies were university laboratory studies, and that classroom evidence was limited (Firth, Rivers and Boyle, 2021).

Interleaving has a particular logic in science, which links back to Chi, Feltovich and Glaser (1981). If pupils practise only energy calculations in the energy topic and only force calculations in the forces topic, they never need to decide which principle a problem requires. The topic heading tells them. Mixed practice, in which pupils must first work out whether a problem is about energy, forces or momentum, builds exactly the principle-based recognition that distinguishes experts. In this sense, interleaving is not only a memory technique but a way of teaching pupils to see problems as physicists do.

Principle 4: Use words and pictures together, carefully

Dual coding is the idea that combining verbal and visual information can improve learning, because the two are processed through partly separate channels (Clark and Paivio, 1991). Mayer's (2009) research on multimedia learning developed this into a set of design principles, such as presenting words and corresponding pictures together rather than separately, and removing interesting but irrelevant material.

Science is a highly visual subject, and good diagrams are central to it: particle diagrams, circuit diagrams, wave diagrams, food webs and graphs. Dual coding at its best means using these representations deliberately, explaining them aloud while pupils look at them, and building them up step by step rather than presenting a complex diagram all at once.

But dual coding is also one of the most frequently misunderstood ideas in this field. It is not the same as "learning styles", the discredited idea that pupils learn better when teaching matches a preferred visual, auditory or kinaesthetic style (Pashler et al., 2008). Nor does it mean adding pictures or icons to every slide. A decorative image that has no explanatory function adds extraneous load rather than reducing it. The test for any visual in a science lesson is whether it helps pupils build the model they need.

Principle 5: Ask pupils to explain to themselves

Two of the techniques Dunlosky et al. (2013) rated as moderately useful deserve more attention from science teachers than they usually get. **Elaborative interrogation** means prompting learners to ask and answer "why?" questions about what they are learning: why does a metal expand when heated? why does the rate of photosynthesis level off at high light intensity? **Self-explanation** means asking learners to explain to themselves how new information relates to what they already know, or why each step of a worked example is taken.

Self-explanation has deep roots in science education research. Chi et al. (1989) studied university students learning mechanics from worked examples. The students who learned most were those who spontaneously explained the examples to themselves, working out why each step followed and how it related to physics principles. Weaker learners read the same examples but did not explain them, and later struggled with new problems. The difference lay not in the examples but in what the students did with them.

This finding connects several strands of the cognitive science story. It explains why worked examples work best when pupils study them actively rather than copy them. It supports the case for retrieval questions that ask "why?" rather than "what?". And it helps build the principle-based

organisation of knowledge that Chi, Feltovich and Glaser (1981) found in experts. In practice, simple prompts are enough to start: "Why is this step needed?", "Which principle is being used here?", "What would change if the mass were doubled?"

Cognitive science and practical work

Practical work is central to science, and cognitive science raises useful questions about how it is designed. A typical school practical asks pupils to follow written instructions, handle unfamiliar apparatus, take and record measurements, and keep in mind what the investigation is meant to show, all at once. From a cognitive load perspective, this is a demanding combination, and the conceptual purpose of the practical is often the first thing to be squeezed out of working memory.

Research on practical work in English schools supports this concern. Abrahams and Millar (2008) observed practical lessons in secondary schools and found that they were generally effective at getting pupils to do what was intended with objects and materials, but much less effective at getting them to think about the ideas the practical was meant to illustrate. Practical work was often "hands-on" without being "minds-on".

Cognitive science suggests some straightforward responses. Teach the key ideas and the method before the practical, so that pupils are not learning both at once. Reduce extraneous load by simplifying instructions, pre-drawing results tables and demonstrating unfamiliar techniques first. Make the purpose explicit: what are we measuring, and what pattern do we expect? And use retrieval afterwards, for example asking pupils to recall the method and explain the result in a later lesson, so that the practical becomes something they remember and understand, not just something they did.

Where cognitive science has been stretched too far

Any widely adopted idea is at risk of what Brown and Campione (1996) called **lethal mutations**: adaptations that keep the surface features of an approach but lose the mechanism that made it work. Cognitive science in schools has produced several, and science departments are not immune.

Retrieval practice as a ritual. A five-question "do now" quiz at the start of every lesson is easy to observe and easy to require. But if the questions test trivial facts, are always about last lesson, or are answered by copying from the board, they have little in common with the retrieval practice studied in research. Retrieval works because pupils make the effort to recall; it works best when spaced; and its value depends on what is retrieved.

"Cognitive load" as a reason to avoid anything difficult. Cognitive load theory is sometimes used to justify removing all challenge, struggle or open-ended work. That misreads the theory, which aims to remove *unnecessary* load so that pupils can engage with *necessary* difficulty. Bjork and Bjork's (2011) desirable difficulties are a reminder that some difficulty is the point.

Explicit instruction versus inquiry as a false choice. The debate sparked by Kirschner, Sweller and Clark (2006) is sometimes presented as a verdict against practical work and inquiry in science. The evidence is more nuanced. De Jong et al. (2023), a group of thirteen learning scientists, reviewed the evidence and argued that inquiry-based instruction can produce better conceptual understanding than direct instruction, particularly when it is supplemented with guidance and direct instruction at the right moments. A meta-analysis of "productive failure", in which students attempt problems before being taught the canonical solution, found a moderate

overall benefit for problem solving followed by instruction compared with instruction first (Hedges' $g = 0.36$), particularly for conceptual understanding and transfer and for older students (Sinha and Kapur, 2021). The authors also found that the order mattered less, or reversed, for younger learners and for general skills.

These findings do not contradict cognitive load theory so much as qualify how it is applied. Expertise reversal already predicts that the right amount of guidance depends on prior knowledge. And a well-designed "productive failure" task is not minimal guidance: it is a deliberately chosen problem, followed by explicit instruction that builds on pupils' attempts. The lesson for science teachers is that the question is not "explicit instruction or inquiry?" but "what guidance, at what point, for which pupils?"

Ignoring what pupils already believe. Cognitive science models often treat learning as adding knowledge to long-term memory. But in science, pupils' long-term memory is not empty: it is full of intuitive ideas about forces, heat, living things and matter, many of them wrong and resistant to change. The EEF's first recommendation for secondary science is to build on pupils' preconceptions (Education Endowment Foundation, 2018). Retrieval practice of the correct answer will not, on its own, dislodge a strong intuitive belief that heavier objects fall faster. Pupils need to confront the misconception, see evidence against it, and practise the correct explanation. Cognitive science and research on conceptual change need to work together.

Forgetting about motivation. Pupils are more likely to think hard about something they find interesting or meaningful. A lesson designed purely to minimise load can be efficient but dull. Willingham (2009) himself argues that people are naturally curious, but that curiosity is fragile and depends on problems being of the right difficulty. Demonstrations, surprising results and real-world puzzles remain powerful tools in science, provided they are used to provoke thinking about the science rather than simply to entertain.

Putting it together: a sequence on specific heat capacity

The principles above are easier to see in combination. Consider a Year 10 sequence on specific heat capacity, a topic that combines a new concept, a required practical and a calculation.

Activating prior knowledge. The first lesson begins with retrieval questions on energy stores, energy transfer and the particle model, all taught weeks earlier. This both strengthens those memories and brings into working memory the knowledge needed to understand the new topic.

Explicit explanation with careful visuals. The teacher introduces the idea that different materials need different amounts of energy to raise their temperature, using a single, well-labelled diagram of two blocks being heated, with the explanation given aloud while pupils look at it. The equation for change in thermal energy, $\Delta Q = mc\Delta\theta$, is introduced with each symbol linked directly to the diagram.

Worked examples, then fading. Pupils study a complete worked example, explaining each step to a partner, then complete a partially worked problem, then a faded example, before attempting problems independently. Those who are already secure move to independent problems sooner.

A purposeful practical. The required practical is introduced after pupils understand what they are measuring and why. Pupils retrieve the method from memory in a later lesson, rather than following a worksheet each time.

Spaced and interleaved practice. In the weeks that follow, specific heat capacity questions appear in retrieval quizzes alongside questions on kinetic energy, gravitational potential energy and power. Pupils must decide which equation each problem needs, rather than being told by the topic heading.

Addressing misconceptions. At some point, the teacher deliberately raises the common confusion between heat and temperature, using a prediction task (for example, which will heat up faster: 1 kg of water or 1 kg of oil supplied with the same power?) to bring pupils' ideas into the open before the scientific explanation is consolidated.

None of these moves is unusual. What makes the sequence coherent is that each step is chosen because of what it does to pupils' memory and understanding, not because it is on a checklist.

Implications for science departments

If science teachers are to use cognitive science well, several implications follow for departments and leaders.

- **Plan for the long term.** Spacing and retrieval work across weeks and months, not within a single lesson. Schemes of work should build in planned revisits to earlier content, particularly the core ideas that later topics depend on.
- **Make retrieval about connections.** Department quizzes and homework should include questions that require pupils to explain links between ideas, not only recall facts.
- **Design resources to reduce extraneous load.** Integrated diagrams, uncluttered slides and consistent representations across the department save working memory for the science.
- **Match guidance to expertise.** Worked examples and scaffolds should be faded as pupils become secure, and teachers should feel free to let confident pupils work independently sooner.
- **Keep practical work and inquiry, but guide them.** Practical work and well-structured problem solving have a strong place in science when pupils know what they are trying to learn from them.
- **Judge approaches by their effect on learning, not their visibility.** A retrieval quiz on the board is not evidence of retrieval practice; pupils' ability to recall and use knowledge weeks later is.

Conclusion

Cognitive science has given science teachers a valuable set of tools. Its core model, a small working memory and a vast long-term memory, explains a great deal about why science is hard to learn and why some teaching approaches work better than others. The evidence for retrieval practice and spacing is strong, including in real classrooms. Worked examples, faded as pupils gain expertise, are well suited to the calculations and explanations that science demands. And the study of how experts and novices differ offers a clear picture of what science teaching is trying to build: knowledge organised around the big ideas of the subject.

But the field's own leading reviews urge caution about how these ideas reach classrooms. Laboratory findings do not always transfer; some popular approaches have little classroom

evidence; and several have been simplified into rituals that keep the form but lose the substance. The debate about explicit instruction and inquiry is also less settled than it is sometimes presented.

For science teachers, the most useful stance is neither enthusiasm nor scepticism but understanding. A teacher who knows *why* retrieval works will design better retrieval tasks. A teacher who understands expertise reversal will know when to stop modelling. And a teacher who sees cognitive science as one lens among several, alongside research on misconceptions, practical work and motivation, will be best placed to help pupils not just remember science but understand it.

References

- Abrahams, I. and Millar, R. (2008) 'Does practical work really work? A study of the effectiveness of practical work as a teaching and learning method in school science', *International Journal of Science Education*, 30(14), pp. 1945–1969.
- Agarwal, P.K., Nunes, L.D. and Blunt, J.R. (2021) 'Retrieval practice consistently benefits student learning: a systematic review of applied research in schools and classrooms', *Educational Psychology Review*, 33(4), pp. 1409–1453.
- Bjork, E.L. and Bjork, R.A. (2011) 'Making things hard on yourself, but in a good way: creating desirable difficulties to enhance learning', in Gernsbacher, M.A., Pew, R.W., Hough, L.M. and Pomerantz, J.R. (eds) *Psychology and the Real World: Essays Illustrating Fundamental Contributions to Society*. New York: Worth, pp. 56–64.
- Brown, A.L. and Campione, J.C. (1996) 'Psychological theory and the design of innovative learning environments: on procedures, principles, and systems', in Schauble, L. and Glaser, R. (eds) *Innovations in Learning: New Environments for Education*. Mahwah, NJ: Lawrence Erlbaum, pp. 289–325.
- Cepeda, N.J., Pashler, H., Vul, E., Wixted, J.T. and Rohrer, D. (2006) 'Distributed practice in verbal recall tasks: a review and quantitative synthesis', *Psychological Bulletin*, 132(3), pp. 354–380.
- Chandler, P. and Sweller, J. (1991) 'Cognitive load theory and the format of instruction', *Cognition and Instruction*, 8(4), pp. 293–332.
- Chi, M.T.H., Bassok, M., Lewis, M.W., Reimann, P. and Glaser, R. (1989) 'Self-explanations: how students study and use examples in learning to solve problems', *Cognitive Science*, 13(2), pp. 145–182.
- Chi, M.T.H., Feltovich, P.J. and Glaser, R. (1981) 'Categorization and representation of physics problems by experts and novices', *Cognitive Science*, 5(2), pp. 121–152.
- Clark, J.M. and Paivio, A. (1991) 'Dual coding theory and education', *Educational Psychology Review*, 3(3), pp. 149–210.
- Cowan, N. (2001) 'The magical number 4 in short-term memory: a reconsideration of mental storage capacity', *Behavioral and Brain Sciences*, 24(1), pp. 87–114.
- de Jong, T., Lazonder, A.W., Chinn, C.A., Fischer, F., Gobert, J., Hmelo-Silver, C.E., Koedinger, K.R., Krajcik, J.S., Kyza, E.A., Linn, M.C., Pedaste, M., Scheiter, K. and Zacharia, Z.C. (2023) 'Let's talk evidence – the case for combining inquiry-based and direct instruction', *Educational Research Review*, 39, 100536.
- Dunlosky, J., Rawson, K.A., Marsh, E.J., Nathan, M.J. and Willingham, D.T. (2013) 'Improving students' learning with effective learning techniques: promising directions from cognitive and educational psychology', *Psychological Science in the Public Interest*, 14(1), pp. 4–58.

- Ebbinghaus, H. (1885) *Über das Gedächtnis*. Leipzig: Duncker & Humblot. English translation: Ruger, H.A. and Bussenius, C.E. (1913) *Memory: A Contribution to Experimental Psychology*. New York: Teachers College, Columbia University.
- Education Endowment Foundation (2018) *Improving Secondary Science: Guidance Report*. London: EEF. Available at: <https://educationendowmentfoundation.org.uk/news/improving-secondary-science-guidance-report>
- Firth, J., Rivers, I. and Boyle, J. (2021) 'A systematic review of interleaving as a concept learning strategy', *Review of Education*, 9(2), pp. 642–684.
- Johnstone, A.H. (1991) 'Why is science difficult to learn? Things are seldom what they seem', *Journal of Computer Assisted Learning*, 7(2), pp. 75–83.
- Kalyuga, S., Ayres, P., Chandler, P. and Sweller, J. (2003) 'The expertise reversal effect', *Educational Psychologist*, 38(1), pp. 23–31.
- Karpicke, J.D. and Blunt, J.R. (2011) 'Retrieval practice produces more learning than elaborative studying with concept mapping', *Science*, 331(6018), pp. 772–775.
- Kirschner, P.A., Sweller, J. and Clark, R.E. (2006) 'Why minimal guidance during instruction does not work: an analysis of the failure of constructivist, discovery, problem-based, experiential, and inquiry-based teaching', *Educational Psychologist*, 41(2), pp. 75–86.
- Mayer, R.E. (2009) *Multimedia Learning*. 2nd edn. Cambridge: Cambridge University Press.
- Mayrhofer, R., Kuhbandner, C. and Frischholz, K. (2023) 'Re-examining the testing effect as a learning strategy: the advantage of retrieval practice over concept mapping as a methodological artifact', *Frontiers in Psychology*, 14, 1258359.
- McDaniel, M.A., Agarwal, P.K., Huelser, B.J., McDermott, K.B. and Roediger, H.L. (2011) 'Test-enhanced learning in a middle school science classroom: the effects of quiz frequency and placement', *Journal of Educational Psychology*, 103(2), pp. 399–414.
- Pashler, H., McDaniel, M., Rohrer, D. and Bjork, R. (2008) 'Learning styles: concepts and evidence', *Psychological Science in the Public Interest*, 9(3), pp. 105–119.
- Perry, T., Lea, R., Jørgensen, C.R., Cordingley, P., Shapiro, K. and Youdell, D. (2021) *Cognitive Science Approaches in the Classroom: A Review of the Evidence*. London: Education Endowment Foundation. Available at: <https://educationendowmentfoundation.org.uk/news/new-what-do-we-really-know-about-cognitive-science-in-the-classroom-eeef-publishes-new-review-of-the-evidence>
- Renkl, A. and Atkinson, R.K. (2003) 'Structuring the transition from example study to problem solving in cognitive skill acquisition: a cognitive load perspective', *Educational Psychologist*, 38(1), pp. 15–22.
- Roediger, H.L. and Karpicke, J.D. (2006) 'Test-enhanced learning: taking memory tests improves long-term retention', *Psychological Science*, 17(3), pp. 249–255.
- Rohrer, D. and Taylor, K. (2007) 'The shuffling of mathematics problems improves learning', *Instructional Science*, 35(6), pp. 481–498.
- Rosenshine, B. (2012) 'Principles of instruction: research-based strategies that all teachers should know', *American Educator*, 36(1), pp. 12–19, 39.
- Runeckles, C. (2021) 'Cognitive science approaches in the classroom – what does the review say?', *Durrington Research School*. Available at: <https://researchschool.org.uk/durrington/news/cognitive-science-approaches-in-the-classroom-what-does-the-review-say> (Accessed: 7 October 2026).
- Sinha, T. and Kapur, M. (2021) 'When problem solving followed by instruction works: evidence for productive failure', *Review of Educational Research*, 91(5), pp. 761–798.
- Sweller, J. (1988) 'Cognitive load during problem solving: effects on learning', *Cognitive Science*, 12(2), pp. 257–285.

Sweller, J. and Cooper, G.A. (1985) 'The use of worked examples as a substitute for problem solving in learning algebra', *Cognition and Instruction*, 2(1), pp. 59–89.

Sweller, J., van Merriënboer, J.J.G. and Paas, F. (2019) 'Cognitive architecture and instructional design: 20 years later', *Educational Psychology Review*, 31(2), pp. 261–292.

Willingham, D.T. (2009) *Why Don't Students Like School? A Cognitive Scientist Answers Questions About How the Mind Works and What It Means for the Classroom*. San Francisco: Jossey-Bass.