

Meet the Chemicals Running Your Classroom

PLAIN ENGLISH GUIDE • THE NEUROSCIENCE

Daniel Willingham said memory is the residue of thought. The biology suggests what is going on here and the system behind the Seesaw, in plain English. This is not a playbook, just biologically grounded principles, for you to use as you see fit.



FIRST, A QUICK REFRESHER

Three systems, one seesaw

Three brain networks run every lesson. Two of them sit at opposite ends of a seesaw and can't both be fully switched on at once. A third system decides which way it tips.

- 1. Focus Mode (the Executive Control Network).** Outward attention, working memory, problem-solving. Active when a student is concentrating hard on a task.
- 2. Reflection Mode (the Default Mode Network).** Inward reflection, meaning-making, identity, imagining what comes next. Active when a student is reflecting or making sense of something.
- 3. The Pivot (the Salience Network).** Monitors the body and the environment, decides what's worth switching for, and drives the switch between the other two.

The pivot only fires for one reason: it detects that something matters. Not just novelty for its own sake. Significance. And significance comes from one of three places.



HOW SIGNIFICANCE GETS DETECTED

Three kinds of mattering

- 1. Personal:** Connects to a student's own history, goals, identity, and what they already care about.
- 2. Social:** Connects to relationships, belonging, and the social dynamics of the room.
- 3. Cultural:** Connects to the practices, values, and shared stories of a wider group the student belongs to.

Miss all three, and the pivot resists activation. Attention stays undirected, and whatever follows is biologically unlikely to consolidate, no matter how clearly it's explained.



A DETAIL WORTH KNOWING

Relevance comes before surprise

There are two ways to activate the pivot. They aren't interchangeable or available to everyone at the same time.

ROUTE 1 · RELEVANCE

Connect new material to something a student already understands or cares about. This is the main route open to a true beginner, since you're less likely to be surprised by something you have no model of yet.

ROUTE 2 · SURPRISE

Once someone has a solid model of a concept, breaking their expectations fires the pivot even harder; a genuine "wait, what?" moment. This works best once there's a model there to violate.

This is why 'productive struggle' can transform a confident student and completely stall a beginner. It isn't the technique failing. It's the wrong route for where that student actually is (van Kesteren *et al.*, 2012).



A COMMON MISREAD

Changing a mind is a threshold problem, not a volume problem

Route 2 above raises an obvious next question. If surprise fires the pivot harder, does more surprise change minds faster? No. Actually, past a fairly modest point, it does the opposite.

THE INTUITION

Bigger contradiction, bigger wake-up call, bigger change. Prove someone wrong hard enough and the model has to update.

WHAT THE EVIDENCE SHOWS

Engagement (of medial prefrontal cortex) drops sharply at very high mismatches (van Kesteren *et al.*, 2012). Direct contradiction of a strongly held belief tends to harden it, not soften it (Festinger, 1957).

The reason is identity, not information. The brain doesn't run separate systems for 'beliefs about the world' and 'beliefs about myself.' Above a certain threshold, a challenge to what someone believes is felt as a challenge to who they are. The mind and body treats identity threats as threats, not just data to rationalise.

DID YOU KNOW

*Here's the counterintuitive part. People with stronger analytical skills are more likely to reject strongly incongruent evidence on identity-relevant topics, not less (Kahan *et al.*, 2017). More horsepower for reasoning just means more horsepower for building a case against the thing they don't want to believe.*

So the variable that predicts whether a mind actually changes isn't the size of the surprise. It's whether updating the model feels less costly than defending it; a question more about relationship and safety, than knowledge. Who delivers the challenge, and whether being wrong here carries any social penalty, does more work than how big the contradiction is.

Changing a belief isn't the same as changing a habit.

- **Beliefs** update through new, high-salience information.
- **Habits** rely on deep reinforcement loops, hence we often repeat behaviours we know are harmful.

Updating a habit can involve **reconsolidation**: memories briefly become editable when recalled. A moderate surprise opens the door for a clean rewrite, but an overwhelming shock just causes fragmented memory rather than a lesson learned.

Note: This brings together memory research and attitude-change paradigms. While it's a logically sound framework, the two haven't been formally tested together in a single study yet.



THE CHEMISTRY

Six chemicals, six jobs

Here's what's going on. Six signals, each doing a specific job, each with a sweet spot.

01 · REWARD AND CURIOSITY

Dopamine

"The surprise meter"

Fires when reality doesn't match what your brain expected. It's an "update your understanding" signal, not simply a pleasure hit, and it also tags whatever it decides caused the surprise, deciding what you get motivated to repeat.

TOO LITTLE: Nothing feels new. No pull to explore anything.

TOO MUCH: Everything feels exciting and nothing holds. Constant novelty-chasing.

02 · AROUSAL AND FOCUS

Noradrenaline

"The volume dial"

Turns focus up or down. A moderate amount sharpens attention. A lot flips the system into threat mode.

TOO LITTLE: Drowsy, disengaged, checked out.

TOO MUCH: Panic. The prefrontal cortex, your reasoning brain, goes partly offline (Arnsten, 2009).

03 · SEESAW MODULATOR [CONTESTED]

Serotonin

"The mood stabiliser"

Thought to help bias whether arousal tips a student toward reflecting or acting on impulse. Worth flagging: its precise role here is still debated among researchers.

TOO LITTLE: Rigid, impulsive, struggles to step back and reflect.

TOO MUCH: Overcautious, difficulty engaging with any challenge.

04 · STRESS AND CHALLENGE

Cortisol

"The stress signal"

In moderate, short bursts, it actually strengthens memory. In large, chronic doses, it breaks the whole system.

TOO LITTLE: Low motivation, flat affect.

TOO MUCH: Stuck in rumination or constant hypervigilance (Vogel and Schwabe, 2016).

05 · ATTENTIONAL FUEL

Glutamate

"The fuel tank"

Powers focused attention, and burns down the longer that focus is sustained.

TOO LITTLE: Can't sustain focus at all.

TOO MUCH: Mental fatigue. The brain protectively shuts concentration down (Wiehler *et al.*, 2022).

Acetylcholine

“The highlighter pen”

Sharpens whatever you're genuinely engaged with and dims the background noise around it, so it's more likely to stick. Alertness alone doesn't release it. Genuine engagement is required (Hasselmo, 2006; Froemke *et al.*, 2007).

TOO LITTLE: Everything feels blurry. Looks engaged, but little is actually being written into memory.

TOO MUCH: Less of an issue on its own. Usually shows up as poor memory despite apparent engagement.



WHERE WILLINGHAM'S MODEL RUNS OUT

It's not what happened. It's what it got tagged as being about.

“Memory is the residue of thought” (Willingham, 2009) is a tidy line. Think hard enough about something and it sticks. The biology tells a more precise, and more chemical, story.

Every time something significant happens, dopamine doesn't just register ‘that was good.’ It tags what caused it, a process researchers call credit assignment (Gershman and Daw, 2017). That tag decides what we are motivated to repeat, and what is treated as worth keeping.

STATUS-TAGGED

The tag lands on the grade, the approval, the finish line. Once that's secured, the content itself tends to drop, especially if it was never the actual object of care.

CONTENT-TAGGED

The tag lands on the idea itself: the puzzle, the discovery. This is what integrates into long-term understanding and lasts once the external reward disappears.

One long-running comparison of Montessori and conventional schooling found Montessori children more likely to credit their engagement to the work itself rather than to grades or approval (Lillard, 2012). It's a plausible real-world glimpse of this tagging difference in action, though worth noting the study didn't test the underlying mechanism directly.

DID YOU KNOW

*In 2025, researchers found that memories aren't stored only in neurons. Specialised support cells called astrocytes turned out to be part of the memory trace itself, at least in mice. Reactivating them alone could trigger recall. Removing a single gene from them could block it (Williamson *et al.*, 2025). A companion study (Dewa *et al.*, 2025) found that astrocytes became primed upon an emotionally salient experience by being sensitive to noradrenaline. On re-encountering salient memory, only those astrocytes were activated, stabilising the memory. It's early (rodent) research rather than classroom research, but it's a striking hint that the biological reality of memory runs deeper than “neurons that fire together, wire together.” Feeling, then, is where learning is decided, not a wellbeing add-on.*



VOCABULARY WORTH KNOWING

Retrieval strength vs storage strength

Two students can both 'know' something on Friday and be in completely different places (then and later).

RETRIEVAL STRENGTH

How easily something comes to mind right now. Can be high through nothing but effortful repetition, and can vanish fast (Bjork and Bjork, 2011).

STORAGE STRENGTH

How durably something is actually consolidated. Depends on whether it was affectively significant at the moment it went in.

A student can ace Friday's quiz on pure retrieval strength and have almost nothing left by half term. That's not a discipline problem. It's the difference between borrowing an idea and owning it.



THE SCIENCE OF SHUTTING DOWN

A stressed brain isn't choosing to forget

Under threat, noradrenaline floods the prefrontal cortex, the seat of reasoning and planning, and weakens it (Arnsten, 2009). Cortisol on top of that can create what researchers call a 'snapshot without a story': the brain still vividly encodes the feeling of panic, the room, the teacher's tone, but the meaning-making system needed to weave those details into the actual content is suppressed at the same time. Worse, high cortisol can also block the remembering of things a student already knew (Vogel and Schwabe, 2016).

DID YOU KNOW

A student who 'blanks' in a test or quiz show on TV usually isn't lacking effort. Their remembering system has been temporarily, chemically, disconnected.



NEURODIVERGENCE, MECHANISM NOT DEFICIT

Two different pivots, not one broken one

ADHD · THE SQUISHY PIVOT

A noisier switching signal, not less attention

On one leading account, lower baseline dopamine means the small bursts that signal "this matters, switch now" have to compete against more background noise. On this view, what looks like a shortage of attention is a switching signal that's harder to activate.

AUTISM · THE HYPER-SELECTIVE SWITCH

A highly selective pivot, not a noisy one

For topics inside a genuine deep interest, the pivot fires powerfully and switching becomes fluid, sometimes remarkably so. That's what hyperfocus is. For generic "everyone's supposed to care about this" cues, the same pivot may barely register anything at all.

Neither is a fault in the machinery. Both are the same pivot, calibrated to different triggers.



Retiring “memory is the residue of thought”

Willingham's line treats the brain like a tidy machine: think about something hard enough, and in it goes. The biology above says that's incomplete. Here's what it gets wrong, stated plainly.

MYTH

If students look engaged and are having fun, they're learning.

REALITY

What they're having emotion about is what has a hope of consolidating. A class buzzing over a competitive quiz may be tagging the competition, not the content.

MYTH

The brain takes in information, processes it, stores it, retrieves it.

REALITY

Attention is allocated by a system responding to personal, social and cultural significance, not a neutral resource manager. Memory is a reconstruction from affective anchors, not a file retrieval.

MYTH

This is just saying emotions matter. We knew that already.

REALITY

The claim isn't that emotions matter. It's that affect is biologically primary: there is no ‘cognitive’ learning that isn't also, underneath, affective - both on forming and when reconstructing memories.

None of this throws out clear explanations or worked examples. It explains the conditions under which they may be effective, including whether short or long lasting.

“The chemistry doesn't ask what you delivered. It asks what mattered.”

This is the science underneath the Seesaw model. More at affectivelearninglab.com.