Learning how to study

Author: Michel Besserve

Some elements to guide you through the fascinating process of learning

Dear Bachelor students,

while you may have stumbled upon the term Machine Learning when looking at our institute's activities, learning is not just for machines! As humans we are endowed with highly efficient capabilities to learn from our experiences, which is also exactly what studying at the university is about. This page aims at sharing with you some perspectives and tools about the process of human learning to support your approach to studying, especially in the first semesters. Many of these tools may prove useful at a later stage of your journey too. As I have myself worked on biological learning, I have come to realize that general knowledge on this topic, spanning multiple disciplines (neuroscience, cognitive sciences, psychology etc...), provides us with principles to study more effectively and find more joy in the process.

A large part of this article is dedicated to the description of the brain's two memory systems: *working memory* and *long-term memory*. Here is why: memory systems are the key resources you need to manage in order to learn efficiently and durably. Indeed, all memory systems have limitations and require special conditions to work optimally. **Managing your memory systems means finding a way to use your memory systems so that they work in optimal conditions and complement each other.**

You can find many of the elements summarized in this article (and more) explained, in a slightly different way, in the book by Barbara Oakley, "A mind for numbers" [1], which provides a good and practical introduction to the topic.

*Cautionary notes:
(1) this page is a work in progress that I chose to make available early on, given the urgency of providing some basic advice to first year students. If you are struggling with your studies at a later stage, this can also give you hints to analyze and rethink your approach to studying.
(2) Please note that the provided explanations contain simplifications which are meant to summarize the most relevant aspects of our current understanding of the human brain. However, more detailed scientific references will be provided a much as possible.
(3) The way your brain works may differ from the main patterns identified by scientific research: this is often referred to as neurodiversity. This text leverages well identified

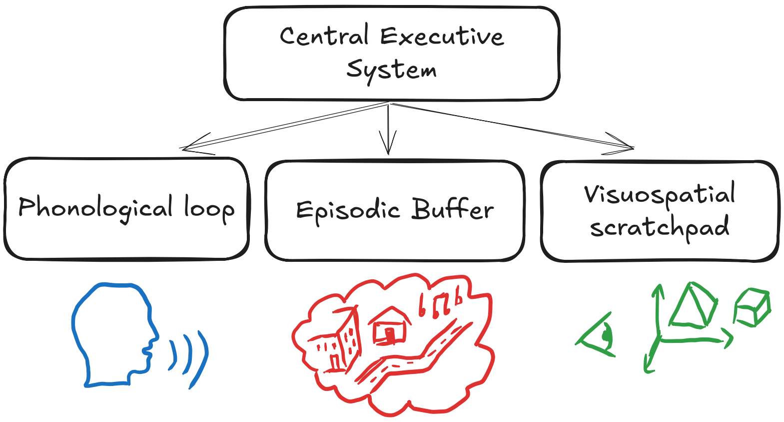
mechanisms playing a role in human learning to help you reflect on your study habits, but you should keep in mind that you have to experiment with yourself to find what works best for you.

Feel free to send me feedback and requests at michel.besserve@tuebingen.mpg.de*

How humans think? The tip of the iceberg

Working memory

What is happening in your head while you are studying? Maybe You try to remember some formulas, perhaps to visualize a concept, perhaps you have an inner voice going trough a sequence of logical steps. All these impressions reflect the use of our "thinking toolbox" that has been named working memory. Psychologists have inventoried important tools in this toolbox, as depicted in the following figure.

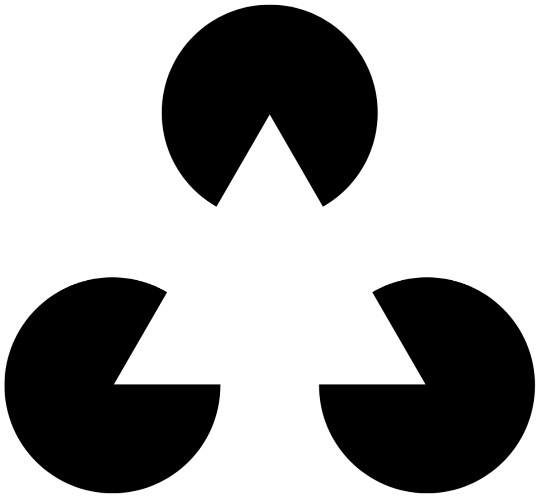


These tools allow to **store temporarily** and **manipulate**: (1) visual information (visuo-spatial sketchpad), (2) auditory information (phonolgoical loop), and (3) link them together into experience-like representations (episodic buffer).
This information can be loaded from **long-term memory**, which we are going to talk about later.

Because working memory is a toolbox, you can go beyond contemplating what happens when you think, you can control how exactly you do it.
Which information is in the working memory is controlled by **attention**.

Attention

Look at the pictureBelow. what do you see?



Perhaps you have seen first these black pac-man objects that are oriented in various ways. Alternatively, you may have identified a white triangle on top of three black disks. This depends on what aspect of the image you have payed attention to: in a more **focused mode**, you may attend to small portions of the image to see individual black pac-mans or you can broaden your attention to the whole picture - switching to a more **diffuse mode** - in which case the specific alignment of the pac man edges gives the impression of a white triangle in the center, occluding black disk lying behind it.

Although at first our attention may chose unconsciously what to attend to, we can control it. For example you can try to alternate voluntarily between the two perceptions described above.

Attention is an important function of our executive system, it selects which information to take into account and which to ignore to achieve our goals. **It also switches** between attending **external stimuli** (what reaches our eyes, ears, skin,...) or **internal representations** (the content of working memory), it cannot really do both at the same time, but the switches can be quick (Nobre and Gresch 2025). Of course, that means that external distractors (such as chat or email alerts on you phone) will deviate your attention from the information in your working memory, and prevent it to work properly (e.g. you may loose part of the information stored in it, and you can even forget what you were doing and never come back to it). That is why **a way to improve your learning performance is to control your environment** and make sure you are not disturbed when you do challenging work.

But of course there are external stimuli that your need to attend to when you are studying: that can be this particular equation written on your lecture notes that you find difficult to understand. Attention has to switch back and forth between this important external information and what is processed in your working memory, for example:

- your recollection of what the professor said about this equation during the lecture,
- the graph that you are drawing on your notebook to summarize the main aspects of the problem,
- etc...

Your attention can be trained to focus on what is most important for you to solve a problem, and it is an important part of what you have to do when trying to assimilate new material. You need to uncover important **patterns/cues** that will indicate:

- how different concepts of the lecture are linked together,
- how an exercise can be solved,
- etc...

The strong limitations of working memory

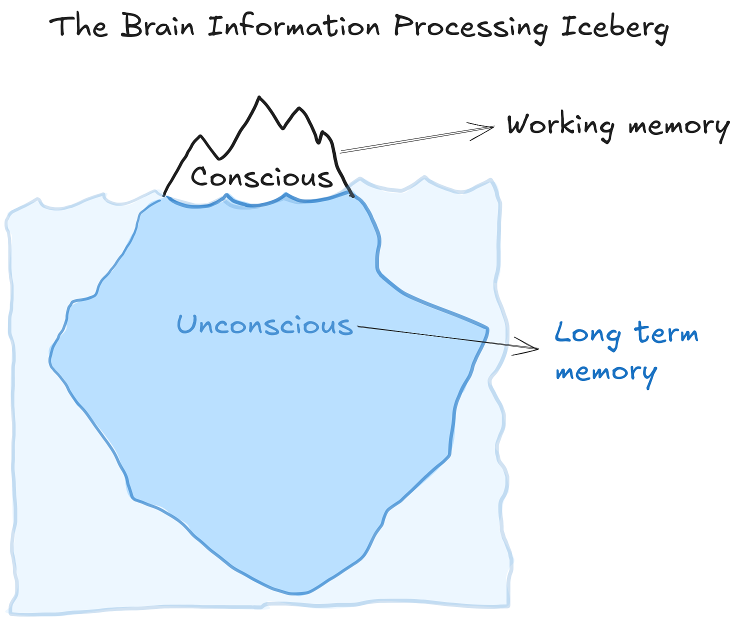
While working memory can be controlled trough attention, it has fundamental limitations:

- **Short-lasting**: information stored in working memory stays there at most few minutes (Hitch and Badeley, 2024).
- **Small capacity**: the number of items that you can store simultaneously is very small, only around 4 items (Cowan, 2010)!
- **Slow processing**: information is processed consciously in working memory, and conscious processing is slow, notably because it is sequential (we cannot split our attention to do multiple tasks in parallel). These sequences are composed of individual cognitive operations that each last at least 200ms.
- **Painful**: like our muscular system, the use of working memory is associated to a sensation of effort, called cognitive load. The more complex and the longer we use this system, the more we get tired. This is not only a subjective impression. When the working memory gets overwhelmed, information processing will deteriorate and lead to mistakes.

That there are some variations of working memory properties across individuals (e.g. some people have a more powerful ability to build visual representations, or can memorize few more items) but there is **little room for improvement**. If we had to select individually with our working memory which key to press on a keyboard (of a piano or laptop), we could only reach 5 key press per second! Of course professional piano players are much faster than that, so there should exist some additional brain mechanisms that we rely on to perform the highly complex tasks that we perform on a daily basis (think of driving, cooking, touch typing on your laptop).
As mentioned in the title of this section, working memory is indeed only the tip of the iceberg...

Long term memory: the powerful engine under the hood

Indeed, while working memory is in charge of conscious information processing, most of every day activities largely rely on automated, unconscious, information processing. You don't have to think about all the individual actions needed for driving your bike or your car when you go shopping. Instead you can think about what you are going to buy, which keeps your working memory busy with a completely different activity. As represented on the figure below, you could see working memory as the tip of the information processing iceberg, while the much bigger part is below the water, unconscious, and implemented by the so-called **long-term memory**.



Long term memory deserves its name as it stores information in neural circuits for months, years, or even your whole life. It comprises:

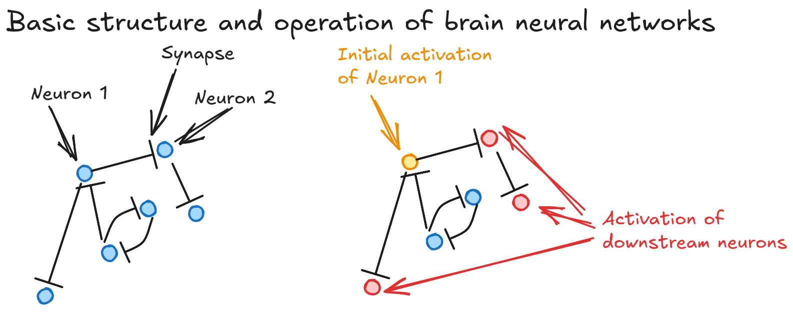
- **implicit memory**: fully automated and unconscious processes that typically don't reach your consciousness (e.g. touch typing, riding a bike...),
- **declarative memory**: a long-term storage for information that you can bring back to your working memory when you need them: facts (e.g. rules and definitions) and events (these are the memories you recover to answer questions such as "where did I leave my keys last night?").

Contrary to working memory, long term memory is has a **fast processing** speed (think of the above keyboard example), **high capacity** (think of the number of words that you know in native or foreign languages), and is largely **effortless** (in particular for implicit memory, it costs only a fraction of the effort needed to execute the same task with working memory). Most importantly, contrary to working memory, the content and quality of long-term memory can be improved by learning. We say that it is **plastic**.

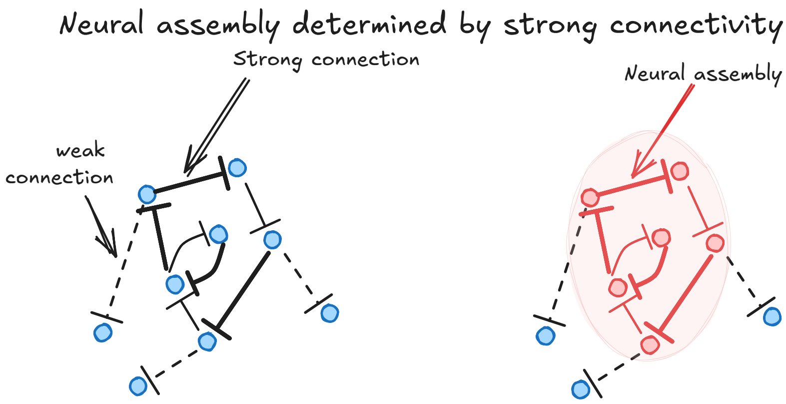
Before we get to concrete properties of these systems, it is good to understand how they work.

The materiality of thoughts: neural assemblies

Our subjective experience (what we think and perceive) as a physical materialization in our brain. What is it?
You probably know that our brain is made of a lot of neurons. Those are organized into a highly complex network: neurons are connected to each other by so-called synapses, and communicate through them by sending electrical signals. To simplify the picture, we can say that neurons are either in an **active** state, and therefore send electrical signals, or is **inactive** and therefore does not receive information. A neuron becomes active if many other neurons send information to it, that is many neurons connected to it are active. As illustrated in the following picture, when one neuron is activated (by another neuron in the brain or a sensory stimulus), it tends to activate neurons to which it send synapses, which will in turn tend to activate further downstream neurons.



Because neurons in the brain are highly interconnected, so-called neural assemblies (or neural ensembles) emerge, where many interconnected neurons get activated together https://doi.org/10.1016/j.neuron.2023.12.008. Although we are making some strong simplifications here, you can consider that the activation of a neural assembly is the physical phenomenon associated to a thought. Inside the group of neurons that constitutes the neural assembly, there can be neurons that are located in different parts of the brain, some encoding visual information, some encoding auditory information, some encoding the action that we will perform next, and much more. This is why we say that the information associated to a thought can be **distributed** across the brain.
What is important to understand is that **thoughts are characterized by the neurons that compose the corresponding neural assembly**, and which are these neurons depends on the number of connections between them and their strength. This is illustrated in the image below where the assembly corresponds to a group of neurons that are strongly and densely connected with each other.



Due to the strong and dense connectivity, such a "strong" neural assembly can emerge by activating any single one of its neurons. That means that is easy to elicit the thought associated to this assembly, e.g. though an external stimulus related to this thought, or an other thought that share so relation (e.g. logical) with it.

What gives rise to a thought?

As we can experience, our thoughts are transient: they have a beginning and an end, and then the next thought takes over. This is because the underlying neural assembly associated to it also emerges and then disappears, but how?
A neural assembly can essentially be initiated by two things:

- another neural assembly (internally triggered), that is, another thought gives rise to it. This is for example what happens if your working memory follows a sequence of tasks: on the first task is achieved, it transmits its information to the next task, and the neural assembly associated to this task emerges,
- an external stimuli (externally triggered), that is, you see, hear, feel something, and the information of these sensations reaches your brain trough sensory pathways, which active some neurons of the assembly. Due to the strong connectivity within the group forming the neural assembly, it is enough for a sensory signal to activate only a few neurons, to have all neurons of the assembly that get in turn activated by this small group of neurons.

But then, how does a neural assembly disappear? This is due to so-called inhibition. We have seen that neuron can activate each other, but they can also inhibit each other, that is, send an electrical signal that prevents other neurons to activate. Thanks to inhibition, the groups of neurons involved in a neural assembly is kept under control, and we can think about one ideas at a time. If there was no inhibition, since roughly all neurons in the brain are connected directly or indirectly, each thought would systematically trigger all other possible thought and our brain would enter a state analogous to an epileptic seizure.
So what happens to neural assemblies when they stop being active? Essentially, when

another neural assembly gets activated, it inhibits the previous one to make sure its activity does not interfere with the new information processing task.

Learning means changing connections

When we study, we have the purpose to learn something. If we are successful that should means that our brain changes, but in which way?
Essentially, that means that we will be able to think differently: remember new concepts, solve problems more quickly, ... Therefore that means that the neural assemblies activated will also change!

So learning boils down to changing neural assemblies. How does this happens? The one thing determining a neural assembly is the connectivity between its participating neurons, i.e. the synapses between them. Synapses between neurons can be weakened or strengthen. Moreover, new synapses can be created, and synapses that become useless can be deleted. There are qualitatively several interesting processes that can be performed by changing the connectivity:

- several neural assemblies can be merged into a single one by creating or strengthening connections between them, in this way to different aspect of a concept can be put together to get a more complete, unified representation of it. This principle is related to **chunking** which we will introduce later.
- a weak neural assembly can become strong by strengthening the connections between participating neurons. In this way it will be easier to activate this assembly with only a weak input to some of its participating neurons. For example, if a neural assembly encodes a concept introduced in the last lecture, it will be easy to remember this concept.

Hebbian learning: co-activate to connect

So *how and when* these connectivity change happen? Here are the answers:

How?: A relatively simple rule turns out to be true most of the time: the connection between two neurons is strengthened when those neurons are activated at the same time. This called **associative or Hebbian learning**, since it was introduced by Donal Hebb in his book *The Organization of Behavior* (1949).

When?: Pretty much each time neurons are activated... Although it is very challenging to measure connectivity changes in the living brain, a lot of evidence suggest that connectivity between neurons is constantly changing as we engage them into any activity. So thinking, practicing an exercise, engaging in any activity can in principle help us strenghten the connections of the assemblies associated to this activity. **But there is a catch**, **the potential increase in connectivity that we get is only temporary**. After a couple of hours or days, these changes may be completely gone, and potentially erased by other connectivity changes that more recent experiences have triggered.

Of course, healthy humans are able to durably learn new skills and concepts. The brain function allowing this has been previously introduced: it is called long-term memory, and it relies on long-term changes in connectivity.

Encoding, recall and consolidation: the intricacies of long-term memory formation

Long-term memory encompasses all aspects of long-term learning: riding a bike, programming languages, foreign languages, manipulating mathematical equations. The brain is a highly complex organs with many subsystems that are specialized in some of the skills that we need to learn. We will not go into these details and keep a high-level perspective on what is required for the long-term acquisition of skills and knowledge. They involved three phases:

- **encoding** is what happens in our brain when we learn something new: new connections are created between neurons involved in this experience, or some preexisting connections (due to other experiences) may be strengthen. As we mentioned above, these connectivity changes are usually temporary,
- **recall** is what happens when you try to remember something (skill, knowledge), it requires to reactive the neural assembly that has been previously created, and it is harder when the connectivity between the involved neurons is week, which is typically the case when the assembly has not been activated a lot. Recall is an important step to strengthen the connections of neural assemblies and therefore make robustly learn the material.
- **consolidation** is what happens when some selected temporary changes in connectivity become permanent. Consolidation typically does not happen when you are actively stuydying (there is typically more encoding and recall). It happens when we rest (this is called *off-line states*), and in particular when we sleep.

While encoding and recall seem obvious functions, the need for off-line consolidation may seem unclear. We can however find some intuitive justifications to this phase:

- consolidation is needed to select among our daily experiences (which have triggered temporary connectivity changes), which ones are worth remembering. Indeed if we would remember everything, we would be overwhelmed by the information from past experiences and unable to exploit it efficiently to act in a changing world. In short, forgetting is important.

- consolidation must happen at least partly off-line to be efficient because it requires making some structural changes to the wiring of our brain. If those changes would happen during activity, it could interfere with the electrical signals that our require by the task at hand. This is analogous to the fact that heavy construction works on the highway or railways are happening during the week-end and the night to minimize perturbations of the traffic.

Basic learning phases for studying

These three phases depend on each other and typically must occur more than once. An alternation of the three phases is necessary for the memory to be consolidated for months or years. In the context of studies, the phases roughly correspond to the following.

Encoding as active reading

Encoding is active reading of the lecture material: trying to understand sequences of logical arguments, the meaning of definitions, the steps of the solution of an exercise. Encoding is done with direct access to the material. It requires an intense use of your working memory and attention focused sometimes on external stimuli (to recognize the important aspects of the lecture material in front of your eyes), sometime on internal representations (e.g. when you are building a visual representation of a concept). *At this stage you can leverage generative AI tools to help you e.g. make sense of some aspects of the material you are struggling with and remember some aspects from previous lectures or courses.* However, keep in mind that these tools are not always reliable and you should typically double check the information (by looking at books, lectures notes, by talking with classmates, TAs and professors). **Warning: generative AI tools should primarily be used when you feel stuck. Most of the work here should be done by your working memory: manipulating concepts, visualising them, checking the logical links between statements...** At the end of a successful encoding, the elements of the lecture notes should *make sense* without external support. You will develop a feeling of understanding when you can easily link together thoughts associated to the various elements of the lecture: one thought naturally leads to the next.

Recall as practice without material

In contrast, **recall happens when you practice with no or limited access to the lecture material and trying to remember definitions, steps of a solution, perform tests**, etc... The amount of information to remember can be controlled: first we try to remember e.g. a single equation at a time, later on we try to write down at once all important definitions and equations of a chapter. Working memory is required to recall the previously encoded knowledge and manipulate it. However, as learning progresses and consolidation strengthens the neural assemblies, recall of well assimilated concepts becomes easier, and many operation can be done quickly and unconsciously: long-term memory takes over more tasks and reduced the cognitive load of working memory. **Warning: do not use generative AI tools for recall, your brain must do the work to learn, that is: it needs to reactivated the encoded neural assemblies for them to become stronger, and easier to reactive the next time**. Remembering requires effort in the beginning, but that is the price to pay to develop new skills. This is the same as anything else: the athlete needs to lift weight to build muscles...

Consolidation as... doing "nothing"

Consolidation happen "in the background" during offline states: when you sleep or when your mind wanders (this could also happen when you do highly automated unconscious tasks, such as driving, cooking, ...). **Warning: watching videos, scrolling on your phone, chatting or not offline states: instead your brain is bombarded with external stimuli and unable to preform consolidation of the encoded knowledge.** You see here that a key step of your learning actually does not happen when you study! However, the way you have studied will be crucial for this step to be successful. Notably, the way you focus your attention during encoding will influence the performance of your long-term memory https://www.nature.com/articles/s44271-025-00309-3. But it is important to know that part of the benefits of your learning will not be seen immediately, rather in the next days/week, as consolidation will have done some improvement to your brain connectivity. Similar phenomena can be observed in the practice of a sport: practice create micro-lesions in the muscles and new muscle fibers are built during the recovery phase, such that the body becomes more adapted to the practice for the next sessions.

Smart repetition of the phases

As mentioned above, encoding, recall and consolidation must be repeated many times. In the context of studies that could take this form (everybody is different so this should be taken only as an illustration to adapt your practice to the requirements of long-term memory):

- active reading of the material within a day after the lecture, and recall practice for simple key elements of it.
- a good night sleep and perhaps some freetime activity (sport, meeting friends,...) for the first round of consolidation.

- after few days you can do a shorter round of active reading and more recall practice without material (exercises)
- again consolidation during sleep will strengthen connectivity on the next nights, **note that without the second encoding and recall, the consolidation phase may have weaken the connection instead of strengthening them, because the new neural assemblies have not been used enough.**
- those steps may be repeated at a couple of weeks later, in a shorten version. Indeed, the more those steps are iterated, the easier they get. At the same time, you need to allocate the majority of your time to the encoding of new material associated to the subsequent lectures.

The **spaced repetition** strategy formalizes that idea that, generally, it is optimal for consolidation to recall the material at spaced intervals of time in shorter sessions of work, instead of spending a large amount of time on the material only once. The time intervals between session must be short in the beginning and my increase almost exponentially (1 day, one week, one month,...), and it is relatively easy to observe that this is optimal when the learning content is fixed: e.g. when learning the vocabulary of a foreign language. But when you learn a scientific discipline, there are many factors to combine when scheduling your learning sessions: your study sessions must integrate the *encoding* of recent material on a weekly basis, while leaving some time to *recall* less recent material, and it must also increase the difficulty of the *recalls*, for example by trying to remember bigger chucks of knowledge at once.

One basic rule for better learning, but many implications

For your studies, the above properties of working and long-term memories lead to one very important principle.

You must train optimally your long-term memory.

Why?

- Long-term memory is the only system that has the capacity to retain the complex knowledge and know-how that you must learn in computer science courses (we have seen the limitations of working memory).
- Once knowledge is optimally consolidated in long-term memory:
  - It is quickly accessible and fast processing, which is particularly useful for exams.
  - It reduces the load of working memory that can focus on the specifics of the situation at hand: the context and peculiarities of the problem you need to solve (again this is particularly helpful for exams). It is analogous to riding a bike at a

> competition: your long-term memory takes care of the details of how you should pedal and hold the handlebar, while you working memory takes care of the tactics (e.g. how to overtake the competitors).
> - It allows you to focus on new knowledge that depend on the consolidated knowledge: e.g. to learn to write a good essay you first need to be able to write letters effortlessly (with a pen or a keyboard).

How? This is the tricky part of course. There are few elements to remember.

Quickly start to work on recall

Encoding is only the first part of the learning process. It is important to spend time understanding the material to encode properly the knowledge of a lecture, but you should start to try to recall early on. You may need to exercise your recall on simple aspects of the lecture before having the feeling that you understood everything. Once this partial knowledge has started to be consolidated, it will be easier for you to come back to encoding, as things will seem easier to follow for your working memory.

Studying by only repetitively reading course material is misleading. If you don't test your recall capabilities, but just read the course material again and again, you will get a feeling of familiarity with the course. Indeed, you will progressively learn to recognize more and more aspects that you have seen previously. **This does not mean that you have learned.** Only recall and practice without material will test that. If you need to be convinced of this point, think about the difference between watching a football game and actually playing. Obviously watching a lot of games will not be enough to play at a good level...

Make (phone free) breaks

We have seen that consolidation happens during so-called offline states: your brain need to stop processing incoming information in order to reorganize.
Experiments have shown that breaks are beneficial in this way. Instead of spending 2 hours staring at the material, make short study sessions with intense concentration of say 25min, and then make a 10min break! Then you can start again for another 25min, etc... This is the basis of the Pomodoro method, which has some physiological basis.

But be careful with the quality of the break, it should be something that puts your brain in a relaxed state, with very diffuse attention, such as:

- have a coffee with your fellow students,
- look at the window and let your mind wander,
- go for a walk,...
  On the contrary, avoid activities that steal attention (notifications, scrolling,...). Better put your phone away and close your laptop to be on the safe side...

Regularity instead of heroism

We have seen that consolidation in long term memory requires repetitive cycles of recalls interleaved with offline states (rest/sleep). To achieve this you need to study regularly (weekly) during the semester. If instead you study only few days before the exam, your knowledge will be lost at the beginning of the next semester. That means that if you don't pass, you will have to study all over again, and even if you pass, you will have difficulties to learn new material that depends on the previous course.

It is therefore better to study regularly, with a weekly amount that you know you can sustain over the semester, instead of putting that same number of study hours right before the exam.
This relates the problem of stress during the exams: due to lack of regular consolidation during the semester, your long-term memory will be able to take over less tasks during the exam, and your working memory is at risk of getting overwhelmed, generating stress.
Instead, if you have regularly consolidated your long-term memory, it will very likely help you getting more exam questions done even if the context of the exam stresses you.

Put variety in your practice

This important last point is more challenging to grasp, and tightly linked to the structure of the neural assemblies that encode our thoughts. We have seen that you can think of each neuron as one specific component of a thought, and the activation of the assembly put these components together to build a coherent representation of a concept.
The recall of this knowledge, e.g. when you practice an exercise, will be triggered when one of these components will be recognized by your brain when you look at the exercise sheet. In order to be able to recall a piece of knowledge in all relevant situations (when it is likely to be useful to solve a problem), it should be possible to activate the neural assembly by recognizing an arbitrary single component among the wide variety that are involved in this knowledge. This means that the underlying connectivity between the participating neurons need to be "dense" enough such that you can activate the whole assembly by stimulating only a few arbitrary neurons associated to it.

In order to do so, you need to design your practice with enough variety such that you will need to recall each concept in a variety of situations, hinting on different aspects of the concept. This will naturally strengthen a variety of connection within the neural assembly.

Overall, you should practice many kinds of on exercises on a same topic, and also, by the end of the semester, to mix exercises on a variety of topics covering the whole semester.
This will help your long-term memory to robustly recall the information, e.g. in the context of an exam, without needing the particular context where you have originally seen it.

References

- Cowan, 2010: https://pmc.ncbi.nlm.nih.gov/articles/PMC2864034/
- Hitch and Badeley, 2024: https://oecs.mit.edu/pub/1rgtz41v/release/1
- Nobre and Gresch, 2025: https://www.sciencedirect.com/science/article/pii/S0896627325004714