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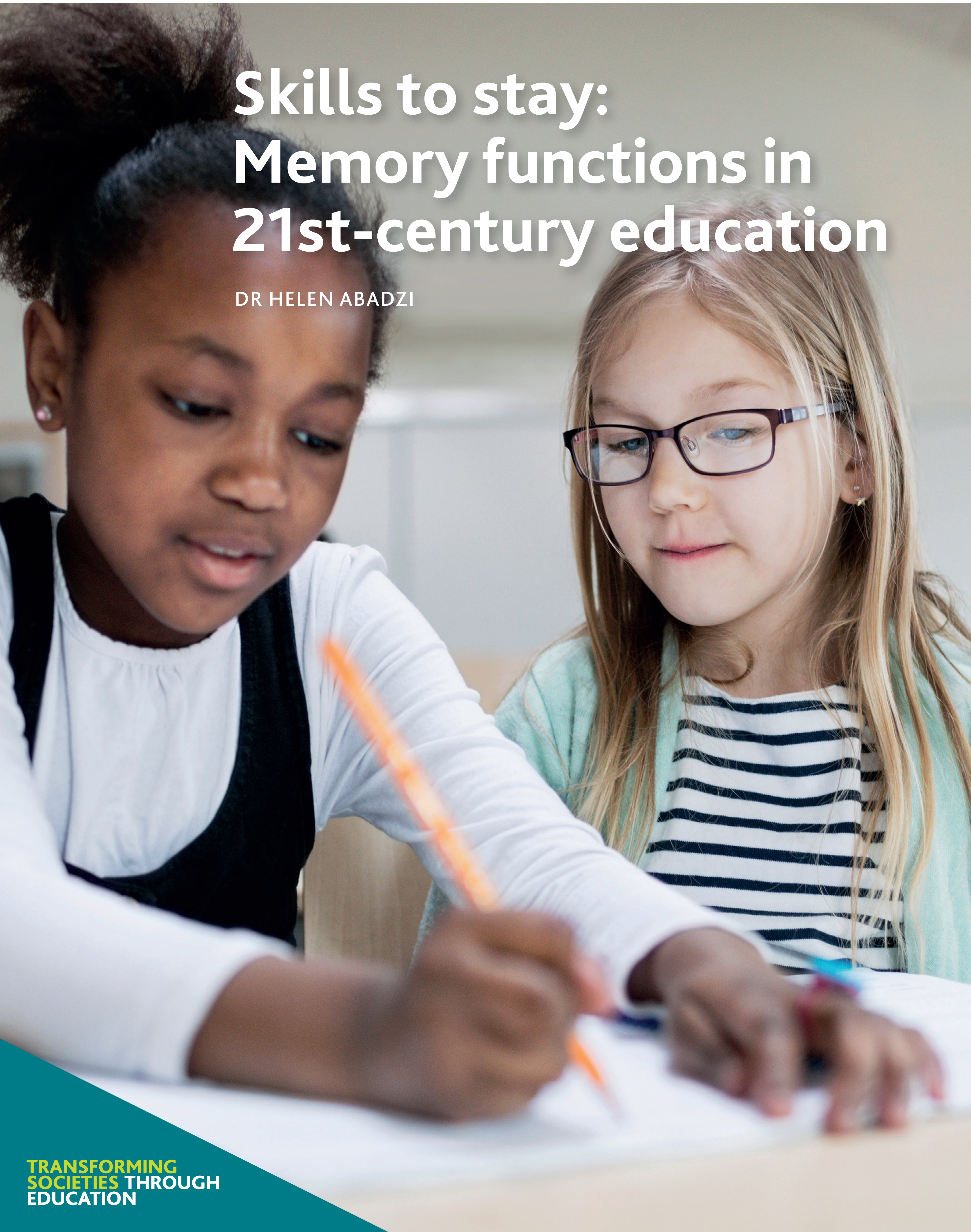

Skills to stay: Memory functions in 21st-century education

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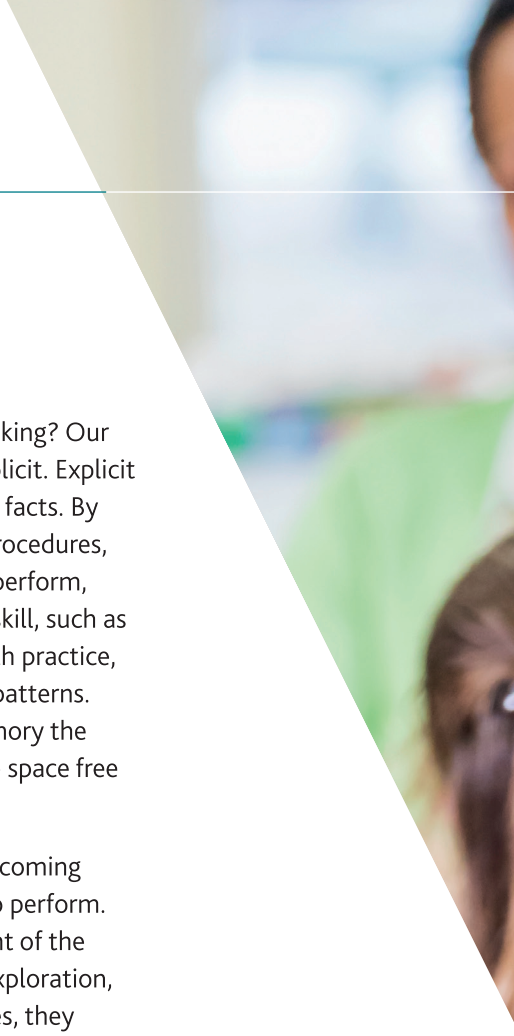
TRANSFORMING
SOCIETIES THROUGH
EDUCATION

To survive in the era of artificial intelligence and global markets, citizens are expected to learn new skills fast and keep up with workforce demands. Accordingly, teachers and policy-makers emphasise complex skills, such as creativity and communication. Many high-income students perform feats of learning, but others, particularly in lower-income areas, do not. To think critically, students must first perform the underlying 'low-level' components instantly and effortlessly: reading, writing, calculating, and fact recall. Our minds today learn through systems that were set up in ancient environments. Paradoxically, the road to excellence is always built on memorisation, practice, and performance speed. To evaluate how to teach complex skills efficiently to the majority of students, it is important to understand memory functions.

The road to excellence is built on basic facts, practice, and increased performance speed.

We have a long-term, relatively permanent memory system, and a temporary one. All of our thinking takes place in the temporary system. Think of a large bottle with a very thin neck. Long-term memory is vast, but our temporary memory – also known as working memory – is minuscule. It holds few items and gets wiped out every few seconds. To think through ideas and make decisions, the data must rush into our minds instantly and effortlessly. And when we learn, information has to traverse this narrow bottleneck and make its way into the vast store of long-term memory. The speed at which information moves from short-term to long-term memory improves with practice. Practice links various items together, and they appear into our working memory as single units.

When students practise and get feedback, individual information items will join up to become larger chunks. Practice speeds up the process and streamlines it. When the information is needed, it is instantly transferred from the long-term to the temporary store, freeing up working memory for complex thinking. Eventually we become able to carry out complex processes effortlessly and automatically.



How are we able to execute skills such as writing while thinking or speaking? Our long-term storage broadly has two types of memories: explicit and implicit. Explicit memory consists of personal recollections and conscious knowledge of facts. By contrast, implicit memory operates below consciousness. It contains procedures, statistical frequencies of various events, memories of watching others perform, and other functions (Squire, 2004; Kalra, 2015). When we learn a new skill, such as playing an instrument, we initially link movements consciously. But with practice, the conscious movements become transformed into implicit memory patterns. They thus become automatic. Then we can recall into our working memory the skills needed for various decisions, while leaving most of this minuscule space free to think through complex ideas.

Because implicit memory is unconscious, it is easily neglected. After becoming proficient in a skill during childhood, we may forget the effort it took to perform. Thus education policies often emphasise complex skills to the detriment of the components therein. Many educational settings recommend fun and exploration, but if students spend much time on relaxed and non-curricular activities, they may read or calculate more slowly and consciously. Such processes will use up more space of the precious working memory and inhibit complex thinking. This is why early emphasis on complexity makes it harder for average students to attain educational objectives.

For correct and creative thinking, students must hold a lot of information and recall it quickly. Curricula must include facts and practice, and students must think fast on their feet.

1. Why memory functions are crucial for policy

It was the end of the graduation ceremony at the Massachusetts Institute of Technology (MIT) in the United States. The new engineering graduates, wearing caps and gowns, were about to leave when a young woman approached some of them individually and politely asked, ‘If you were given a piece of wire, a battery, and a flashlight bulb, could you light the bulb?’ Most of the alumni quickly answered ‘yes’, as this should be a simple task for an engineer. But, when given the items, only a few could do it (Cromie, 1997[2]).

The failure of the MIT graduates has perplexed educators and given rise to derisive comments. If elite engineering graduates cannot connect simple wires, what is the value of their education? Practical mechanics, who are good with their hands, seem at least as competent.

But the example highlighted the need for practice and the unconscious nature of fluent performance. The graduates had studied diagrams and mathematics, so they had to think consciously to connect a lightbulb. But a few had done similar tasks extensively, so they could act without warning.

Life demands that we are able to instantly calculate savings at a supermarket, guesstimate loan costs, avert a driving emergency, or answer something in a language we once knew well. Our mind must be ready to perform certain skills at a moment’s notice, and must often perform all of these tasks in quick succession in order to handle challenges and make the right decisions in minutes, if not seconds. How can students be trained most efficiently to carry out these functions?

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[2] See, e.g., <https://www.youtube.com/watch?v=aIhk9e-KOLzQ>.

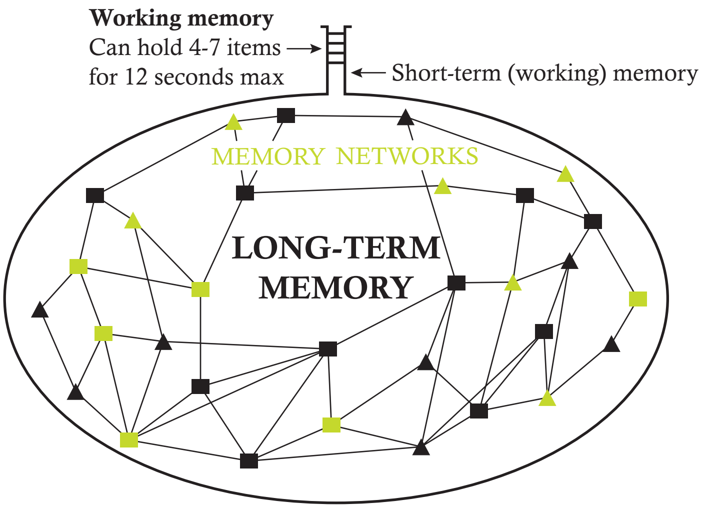
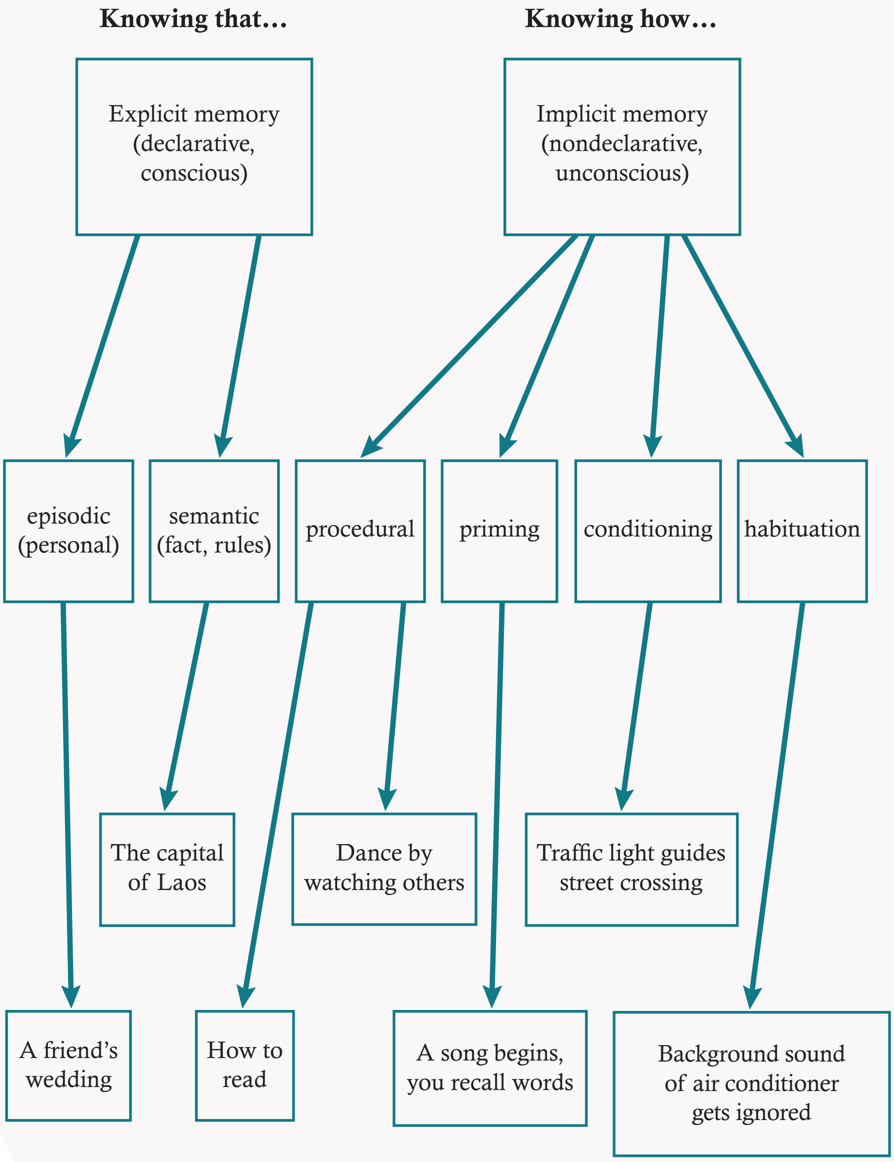


Figure 1: Long-term memory is vast

2. Modern education relies on brains built to serve ancient needs

Memory has evolved to supply organisms with critical, just-in-time information needed for survival that must be stored somewhere (Klein, Cosmides, Tooby, & Change, 2002; Todd, Hertwig, & Hofrage, 2016). Humans inherited the memory system of very ancient animals and enriched it with layers of complex reasoning. Research is ongoing, but important memory functions are well understood (Baddeley et al., 2015).



[Squire, 2004, revised]

Figure 2: Explicit and implicit memory

3. Explicit and implicit memory: Conscious vs. 'mysterious'

Our explicit memory gives us conscious access to events in our lives and of facts or rules. By contrast, our implicit memory acts below the surface. Parts of our brain silently collect frequency statistics, extract patterns, and somehow push this information into our conscious working memory.

The two long-term systems contribute different features to possibly all our tasks. To express important thoughts on social media, for example, we must tap at keyboard keys or hold a pencil in a certain way to write. And if you head for work, you can predict from past experience what the commute will be like. However, we cannot easily explain how we perform certain actions or why we make certain choices. Perhaps due to the evolution from animal to human memory, connections to the explicit system are tenuous. This may be one reason why we do not even realise that implicit memory exists. But to optimise educational attainment, the two long-term memory systems have slightly different learning requirements that must be met.

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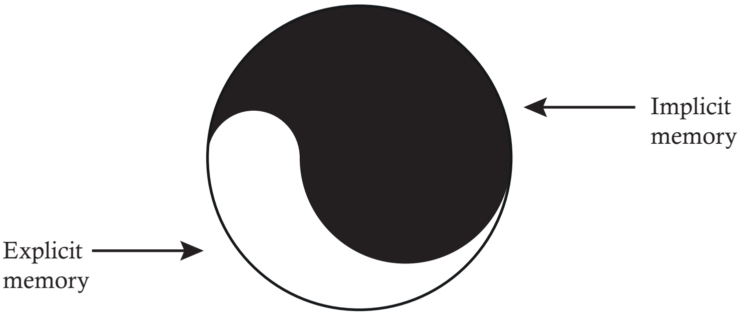

Figure 3: The yin-yang of long-term memory

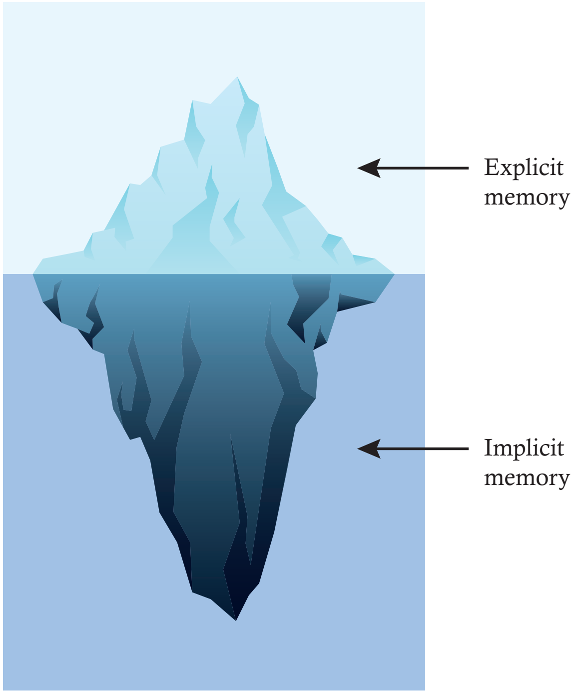

Figure 4: Explicit memory can also be represented as the tip of an iceberg

4. Learning for the explicit memory: the role of ‘chalk and talk’

Our explicit memory learns as we witness events. The events create personal recollections (episodic memory) and convey information and rules that form semantic memory. Biological processes consolidate the information into intricate memory networks that enable retrieval. When new items are few, we may learn them effortlessly, but when there are too many for easy consolidation, practice and repetition are needed. Many techniques exist to minimise effort (see Brown et al., 2014).

Schools effectively create semantic memory through ‘chalk and talk’ – the traditional teaching method of a teacher presenting to the classroom. Curricula and textbooks, whether for classroom or for distance learning, are typically written for this purpose. To be remembered, an item must become embedded in a network, alongside similar concepts. To be retrieved, the previously consolidated path must be followed. Items may be forgotten because other items may overwrite them (Perfect, Moulin, Conway, & Perry, 2002). Semantic memory permits conscious searches and retrieval (Reisberg, 2013). Then, for example, we know that the capital of Laos is Vientiane.

5. Learning for the implicit memory: experience, practice, fluent performance

Our implicit memory also learns from the environment but retains slightly different features. We effortlessly learn how to open a door, and we become conditioned to use similar movements whenever we are in front of one. Similarly we become conditioned to carry out various tasks voluntarily or involuntarily when we see the right cues, with little or no conscious intervention: we *know how* to do something. While it is possible to discuss explicitly the tacit rules encoded into implicit memory, people often find it difficult to do so (Reber, 1993; Stadler & Frensch, 1997; Barrett, Tugade, & Engle, 2004; Soto, Bassett, & Ashby, 2016; Buchner & Wippich, 1997).

One way to retrieve implicit memory contents is through *priming*. For example, you have heard your country's national anthem many times, so the music helps the words effortlessly pop into your working memory. The first stanza is a cue that 'primes' you to sing the second. Priming effects may last up to a year (Perfect, Moulin, Conway, & Perry, 2002). A television commercial may 'prime' viewers to reach for a product on supermarket shelves months after it was viewed.

People are able to watch a performance like a dance and imitate it, but only up to a point. Complex sequences require conscious, step-by-step instruction, followed by practice and feedback (Foerde & Shohamy, 2011). To learn to play the piano, for example, a teacher may show how to touch various keys, and students adaptively imitate the movements. Execution is initially slow and effortful. But with practice and feedback, sequences are rearranged, and the performance speeds up (Anderson, 1982; Song, Howard, & Howard, 2007; Willingham & Goedert-Eschmann, 1999; Willingham, Salidis, & Gabrieli, 2002). Individual items get linked into ever-longer chains – small chunks join up and become large chunks. There is an initial period of fast improvement, followed by slow, step-wise improvement. Trial and error gradually create an efficient performance sequence, followed by mastery (Speelman & Kirsner, 2005).

Trial and error gradually create an efficient performance sequence, resulting in proficiency.

Continued practice somehow transforms conscious performance into an implicit memory task (Soto, Bassett, & Ashby, 2016; Janacsek, Fiser, & Nemeth, 2012). You execute effortlessly, although you can monitor your actions and can change them. The sequence becomes automatised; it is now a *skill*. You can talk and drive, and comment on a text while reading it. And whenever the skill is needed, you can retrieve it and perform it.

Stability is crucial. Explicit memory is subject to significant forgetting, but implicit memory is more durable. Riding a bike, knitting, and reading are skills that are not normally forgotten when not practised. Performance may slow down, but even after 12 years there should be familiarity (Larzabal, Tramoni, Muratot, et al., 2018). Some people are better than others in learning implicit tasks, but this memory function is not closely related to intelligence (Xue, Chen, Jin, et al., 2006; Kalra, Gabrielli, & Finn, 2019).

However, implicit memory has certain peculiarities. Information encoded in semantic memory can transfer and be used to solve many kinds of problems. But skills encoded in implicit memory rarely transfer to other tasks, even with identical stimuli (Szpiro, Wright, & Carrasco, 2014). We cannot transfer the skill of piano playing into typing, although though the movements are almost the same. The stimuli linking these movements are entirely different. To optimise the use of implicit memory, all these issues must be considered.

Young children depend on implicit memory to learn languages and manage their environments, so their brains easily gather statistics, detect patterns in them, and carry out actions. Therefore, ‘digital natives’ become adept in operating devices, but they may not understand the information they see; semantic memory matures only in the primary school years (Finn, Kalra, Goetz et al., 2015; Ofen et al., 2017). It is often easier to demonstrate to small children how to do something rather than explain the process.

6. Working memory is short, fleeting, and requires skills automaticity

The effortless performance possible through implicit memory helps overcome a significant roadblock: working memory limitations. It enables complex cognition and decisions (Ramkumar, Acuna, Berniker, et al., 2016).

Working memory evolved to give animals critical information for instant use, thus it contains what is in your mind right now. Unlike the infinite capacity of long-term memory, it is very short: it holds between four and seven items, for perhaps twelve seconds. There are many models, but the 1950s models assign some numerical values and are easier to understand or apply (Migliore et al., 2008). It is therefore a bottleneck that affects our explicit memory and limits what we can learn from the world around us: we have just a few seconds to process the information. If we understand a message, it may get consolidated into long-term memory. But if we are distracted, if we search for words, if we read and write slowly or understand slowly, working memory gets wiped out. Then we must read or calculate again. And if a message is spoken once and we understand it too slowly, we lose it forever.

Working memory is an unconscious mechanism, and we do not notice its existence. We can get a glimpse when we retain an item, such as a phone number, for temporary use. Someone starts talking to you, and suddenly the number vanishes. Similarly, you get interrupted while chatting, and then you say, ‘What were we talking about?’ Educators and policy-makers often disregard working memory. Curricula and policies on teaching students implicitly assume instant and simultaneous processing of sentences and pictures in books.

Fluent skills circumvent working memory (Larzabal, Tramoni, Muratot, et al., 2018). Linked items pass through as single chunks. They give us precious time to think and decide. Ease is crucial because the brain dislikes protracted mental effort (Mizuno et al., 2011). We may read an article in a foreign language, stopping repeatedly to look up words. But then working memory gets repeatedly effaced, so we may find it hard to retain the gist. Students who process slowly must put in more effort, and they may dislike difficult work. Learners are more likely to become self-directed when information flows relatively effortlessly through their working memory.

Working memory can contain and evaluate large quantities of information, as needed by the demands of globalised economy. But these must become long strings of connected units, instantly recalled – and this is only achievable through many hours of continuous practice and rearrangement of units. Automaticity has the extra benefit of reducing mental stress and potentially making subsequent learning more enjoyable (Crawford et al., 2020).

Automaticity in various processes influences our strategies. Our thoughts and actions are shaped by what we can do most easily. Unconsciously we resort to the sequences we perform more fluently; actions that are more efficient but require effort overload working memory and are unpleasant. For example, proficiency in using Excel greatly facilitates account-keeping; but people who must spend days learning and mastering basics may stick with paper and pencil, because they already perform the procedures fluently.

7. Processing speed is a pillar of education

The short time-space of working memory has an important educational implication: speed is indispensable for learning and performance. We must receive and process multiple items within a few milliseconds in order to analyse and think critically. We must also know a lot, because there is no time to look everything up on the internet. In a store we may recall the multiplication tables to estimate unit costs rather than search for a calculator. By contrast, slow processing fills the working memory with burdensome decisions.

> ***Speed is indispensable for learning and performance – slower processing may contribute to cognitive overload, failure, and dropout.***

An important lesson from memory functions is that the fastest and best-connected information wins. Students need to automatise multiple skills and perform them effortlessly, to reduce their footprint into working memory. Children must read, write, and calculate rapidly, without hesitation. Engineering students must similarly solve differential equations in order to attend to the reasons for their usage. Cooks must lay out and use food ingredients without too many conscious decisions.

The implications for testing are enormous. It is not sufficient to just *know* something – we must be able to retrieve the prerequisites to answer a question within milliseconds.

The consequences of these mental processes are far-reaching. Students of elite secondary schools are assigned more exams and writing papers than students from more disadvantaged backgrounds. They thus get more practice which makes them faster, and so at a university, they have to work less than graduates from poorer schools (Vieru, 2015). Slower processing may contribute to cognitive overload, failure, and dropout.

Little research has been carried out on the number of hours needed to attain fluency benchmarks in school tasks. Competent third-grade calculations and reading depend on retrieval of associations between the visual symbolic and phonological forms (Fuchs et al., 2015). Research suggests that students should be reading 45 to 60 words correctly per minute in all languages and scripts in order to become comprehension-ready (Abadzi, 2017; 2013). They should carry out 11–19 correct mathematical operations per minute in Grade 3 (Year 4 in the UK) (Fuchs et al., 1998). For more advanced subjects that also require procedural fluency, benchmarks could also be set and refined. Children's homework time ought to be used to speed up and consolidate previously taught content rather than learn new content.

8. Some methods became traditional because they are effective

Practice in survival skills has been used since the dawn of civilisation. Archeological excavations have repeatedly found students' practice materials, and references to reading speed exist in ancient Greek texts (Cribiore, 1996). Before books existed, ancient students memorised texts that they could later bring into working memory and apply to various circumstances. Some practices turned into traditions because they work. Contemporary societies are better educated, and well-to-do children are exposed to many exciting events, so their motivational system may find practice boring by comparison (Damrad-Frye & Laird, 1989). Practice may be regarded as 'drill and kill', and text memorisation may be deemed retrograde. Homework may be abolished. The easy procedural skills of 'digital natives' may lull parents and policy-makers into believing that also average students can skip the skills formation process and go on to complex topics.

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9. Implications: prerequisite, component skills are easily neglected

The nature of memory has critical implications for learning outcomes. Learning tasks must be configured to fit the very limited processing space of working memory. This means that they must be compiled into ‘subroutines’ that will be executed rapidly. Conceptual explanations certainly help, particularly older students, but they are no substitute for practice. The MIT alumni discussed in the beginning of this paper were likely very fluent in complex mathematical operations, taught through explicit memory, and knew a lot about electricity. But this did not help them wire small devices without notice.

The unconscious nature of most memory tasks creates powerful illusions (Simons & Chablis, 2011). Memory functions are rarely taught in colleges of education, so they remain inscrutable. Sometimes speed has negative connotations, along with ‘mindless’ recitation. But practice does not have to stay ‘mindless’ – as students speed up, they should get tasks that increase the cognitive load in working memory (Sweller et al., 1998). Assignments should demand applications, conclusions, and transfer for solving new problem types. Some school systems do not progress to this stage, and students are only expected to memorise and recall certain items. This may be one reason why the invaluable ability to sequence items verbatim has earned itself a bad reputation.

Many school assignments should aim at practice for fluency. Others should demand inferences, applications, and transfer to new problem types. High-achieving schools should do both.

10. Visions about globalised learning must consider memory functions

Every day, somewhere in the world, there are debates on the best ways to educate students, given the globalized needs for highly skilled, flexible, life-long learners. Prominent arguments include:

- ***Tradition vs innovation.*** Some educators insist that children must first and foremost learn the three Rs (*r*eading, w*r*iting, and a*r*ithmetic). Others think that innovation can leapfrog traditional learning: *why should children learn facts when they can look them up on the internet? Orderly classrooms with students repeating information or taking tests are an anachronism; textbooks are unnecessary.* Learning should be active, through fun and creative projects. Therefore, teachers should merely be facilitators. Students are expected to become co-creators of knowledge, not empty vessels into which knowledge is poured.[2]
- ***Critical thinking vs. facts.*** Parents or policy makers may prefer to see children perform something useful rather than just pass exams on various subjects. Accordingly, some schools may announce that their mission is not to teach facts, but to engage students in critical thinking. Students spend much time doing experiments and meaningful activities, and in collaboration and communication. This school of thought has given rise to competency-based curricula (Roegiers, 2006), which focus more on the application of knowledge and less on the acquisition of information.

Well-to-do families tend to facilitate basic skills of their children and push them into feats of performance. Such children then as students may then benefit from projects and creative activities, because they are likely to have a more solid foundation upon which to build, while those who get less home preparation may still struggle with basic tasks. The higher attainment of the better-off students has influenced curricula to focus on that demographic, and there is a resultant learning crisis worldwide, the reasons for which are unclear to many. With the rise of pandemics and school closures to avoid illnesses, the better-off may greatly outpace the poorer performers.

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[2] <http://newint.org/blog/2015/02/12/education-system-compliance/#sthash.t4gmTNaE.dpuf>.

11. Policy recommendations: fluency as a learning objective for every education level

Despite individual differences, certain rules of learning are universal. Probably every course and subject has material that must be learned fluently, often in some order. Time must be dedicated explicitly for that, in order for complex concepts to become easier to grasp.

Practice is effortful, and some children will try to avoid it. However, much has been learnt from videogames about the motivational system and the tendency to persist in tasks that are initially hard. Rewards are initially frequent and given for easy tasks, but they become sparser as difficulty increases. If videogames can be addictive, so too can maths exercises. Computerised media, in fact, may be very suitable means to attain basic skills, if software is developed according to research (Pitchford, 2015). Execution times can also be obtained for various tasks, including solutions of algebraic problems.

Learning research also shows various ways to facilitate consolidation. Spacing and interleaving of information can be used more systematically by curriculum designers (Kornmeier et al., 2014; Szpiro et al., 2014; data must be collected on execution and retention rates for various curricular topics). Sleep consolidates memory; children could take naps after school and before they start homework (Yang et al., 2014). By contrast, multitasking inhibits consolidation (Junco & Cotten, 2012).

School systems must make sure that nearly all children automatise the skills they will need for more advanced work as quickly and efficiently as possible. Curricular and extracurricular activities should provide opportunities for executing increasingly complex texts and calculations. Beginner reading and maths books must offer much practice to letters or number magnitudes. Testing should include processing speed components, potentially measured as items per minute. All children should continually improve on reading and calculation speed to attain critical thinking. Skill delays arise early, and are rarely remediated.

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Teachers should ensure acquisition of the invisible skills through step-by-step instruction and practice. They should give and expect completion of practice-related homework. Memorisation of important sequences constitutes durable fluency and enables students to bring ready-made chains of information into working memory. They could encourage memorisation and use of content such as the multiplication tables or verb conjugations in foreign languages.

International agencies often erroneously advise governments appealing to the lower-income or educationally vulnerable demographic to de-emphasise 'traditional' book learning and use innovative pedagogies to teach the needed skills explicitly (Abadzi, 2015). Experts often predicate new skills for the globalised era, but they rarely understand the parameters of human memory. Policy-makers considering alternatives should ask for a rationale based on memory functions. The learning needs of the average and below-average learners must be prioritised.

New learning paradigms for globalisation are seductive ideas, but they run into the realities of 'mysterious' memory functions. Education faculties worldwide must teach these. To alleviate the learning crisis, students need fluency early on. Then complex performance may be as simple as wiring a bulb with a battery.

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