THE CENTRE FOR INDEPENDENT STUDIES

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CIS Education Program

Some Critical Thoughts about Critical and Creative Thinking

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Contents

Executive Summary

- Teaching students to engage in critical and creative thinking attracts near-universal approval. However, that approval's protagonists almost never indicate any general cognitive strategies they themselves learned to use when engaging in such thinking. The absence of such strategies suggests that teachable, general, critical and creative thinking strategies do not exist. Equally absent are concrete examples of students engaging in critical and creative thinking following teaching instruction aimed to specifically develop these capabilities.
- A suspicion of the non-existence of such strategies and examples is strengthened by the paucity of data from randomised, controlled trials providing evidence of an increase in critical and creative thinking following instruction. Such data are essential prior to the introduction of any new instructional procedure.
- While humans do engage in critical and creative thinking, it would prove impossible to teach the relevant strategies if they are innate. Innate thinking strategies allow creative thinking without specific creativity instruction. Evidence of creativity without instruction comes from another, non-human source of creativity — evolution by natural selection.
- Normally considered a biological theory used to explain the diversity of life, evolution by natural selection can also be considered a natural information processing system. Evolutionary theory may provide us with a useful analogy to the human cognitive system, assuming that human cognition is another example of a natural information processing system. Such an analogy throws light on the place of creativity in human cognition.
- From an information processing perspective, both evolution by natural selection and human cognition can be described by five basic principles concerned with how novel information is acquired, how it is processed and stored, and how stored information is used to govern action that is appropriate to the environment. The principles are innate to humans. They are acquired unconsciously and so cannot be taught. The first two principles, concerned with how novel information is acquired, are directly relevant to issues associated with critical and creative thinking.
  1. The first principle assumes that all novel information has a random generate-and-test process at its base, consisting of random mutation in the case of evolutionary biology and random generate-and-test during human problem-solving. It is suggested that random generate-and-test — which does not need to be taught — is an essential engine of creativity.
  2. The second principle indicates that information can be efficiently transmitted by reproduction in the case of evolutionary biology or by communication between people in the case of human cognition. Once that relevant information has been created by a random generate-and-test process, it is vastly more efficient to obtain it by transmission from a suitable source than to create it in the first instance. The ability of humans to efficiently transmit information to others is arguably our most important evolved characteristic.
- These characteristics of the basic nature of creativity, along with other important aspects of human cognition, are almost always ignored by those advocating the incorporation of instruction in critical and creative thinking into curricula.
- Current attempts to measure students' critical and creative thinking skills also characteristically make no reference to human cognitive architecture and consequently are deficient.
- This paper argues that the only way in which critical and creative thinking can be enhanced is by increasing the domain-specific knowledge base to which the innate and random generate-and-test engine of creativity is applied. Accordingly, the function of education is to enhance a knowledge base. With an extensive knowledge base, critical and creative thinking will follow naturally and automatically.

Introduction

Creative thinking is defined as novel thinking that is useful. The related concept of critical thinking requires assessing statements and situations in a manner that allows reconsideration of stated views. While these definitions are abstract, curriculum documents that describe critical and creative thinking almost invariably are written in this highly abstract form with no reference to successful thinking strategies that the writers have in mind— or even concrete examples demonstrating such thinking.

Nevertheless, despite the lack of concrete details, it is frequently argued that critical and creative thinking is a "twenty-first century skill" that is far more important to us than to previous generations. It is suggested that critical thinking has become even more critical because we are constantly bombarded with information, including disinformation such as fake news and conspiracy theories.

In addition, the need for innovation gives rise to a political emphasis on creativity in nation-building. For instance, the Australian government's 2015 National Innovation and Science Agenda specifically sought to produce an 'ideas boom' through, among others, school education reforms to promote creativity and innovation. This apparent urgency is despite the Global Creativity Index 2015 ranking Australia the most creative economy in the world.

The rationale for heightened attention on creativity and critical thinking is their alleged role as the 'new basics' in employment. For instance, it is claimed that over just a three year period, employers increased the demand for critical thinking skills by 158 per cent and creativity by 65 per cent — and that employees who demonstrate these skills attract around $7500 and $3000 more in earnings respectively each year in early career jobs.[1] Accordingly, high-stakes hiring and enrolment decisions are now commonly determined by performance in generic critical thinking assessments, such as Pearson's Watson-Glaser Critical Thinking Appraisal instrument.

Many people are therefore in favour of teaching critical and creative thinking in schools.[2] It is frequently assumed that a failure by students to engage in critical and creative thinking can be rectified either by including a generic Critical and Creative Thinking subject in the syllabus or by emphasising such thinking in all curriculum subjects. Indeed, it would now be difficult to find an educational establishment that did not include the development of critical and creative thinking skills in one form or another in its mission statement.[3]

Moreover, proponents urge that students' capability to think critically and creatively can, and should, be measured in assessment tools. For instance, the OECD's PISA 2022 includes a 'Creative Thinking' module, and Australian policymakers have been advised to consider assessing critical and creative thinking in annual NAPLAN testing[4] —a point to which this paper will return in the section below: **Measuring critical and creative thinking**.

It is obviously desirable for students to engage in critical and creative thinking. Unfortunately, the desire to instil critical and creative thinking tends not to be matched with knowledge of how humans learn, think and solve problems; known as human cognitive architecture. Indeed, human cognitive architecture is seldom mentioned in tracts endorsing the teaching and measuring of critical and creative thinking.

The upshot has been numerous recommendations that are more likely to interfere with the acquisition of thinking skills rather than add to them. Since critical and creative thinking strategies are almost never in evidence, the most common recommendation is to have students attempt to solve difficult, novel problems that are simply assumed to increase critical and creative thinking skills. The fact that there is a large body of evidence indicating that students learn to solve complex, novel problems more easily by studying worked examples that demonstrate possible solution steps rather than solving problems themselves[5] tends to be ignored. Problem solving increases cognitive load — a burden that is only suitably reduced by studying worked examples.

The inevitable consequence is that, despite decades of effort, there are no bodies of evidence indicating successful teaching of general thinking skills. Because critical and creative thinking are cognitive processes, they should never be taught without knowledge of our cognitive architecture. As indicated next, that architecture belongs to a class of information processing systems called 'natural information processing systems'.[6]

Natural Information Processing Systems

Human cognitive architecture[7] is concerned with the structures and functions required to allow humans to process information. Rather than beginning with how humans process information, an overview of how information is processed in the natural world will throw light on human cognitive architecture.

There is a natural information processing system that historically has been vastly more creative than anything humans have managed to produce. That system is evolution by natural selection, an information processing system that has created all species and all structures and functions in the biological world. It provides an example of creativity that humans have not matched — and most probably will never match. But we do know the procedures used by biological evolution, and those procedures may be analogous to the procedures used by humans during critical and creative thinking. A consideration of that analogy may provide us with a better understanding of human cognitive architecture and the ultimate sources of our own creativity. Table 1 summarises the analogy.

Table 1. The Analogy Between Evolution by Natural Selection and Human Cognitive Architecture

Evolution by Natural Selection	Human Cognitive Architecture
Generate novel information by random mutation	Generate novel information during problem solving by random generate-and-test
Transmit information during reproduction	Transmit information by communicating between people
Use the environment via the epigenetic system to determine the location and number of mutations	Use a limited capacity, limited duration working memory to process information from the environment
Store useful information permanently in a genome	Store useful information permanently in long-term memory
Via the epigenetic system, use the environment to switch genes on and off to determine phenotypes	Use the environment to determine which elements of stored information are transferred to working memory to generate appropriate action

Evolution by Natural Selection

Evolution by natural selection is most commonly, and of course appropriately, considered as the major theory explaining the various forms of life. But the theory also can be thought of as a natural information processing system. By considering a genome as a store of information, we can analyse the associated information flows to determine the sources of creativity that characterise biological evolution. Those sources of creativity can be described by five basic principles.[8]

1. The first principle is that all biological variation within, and between, species can ultimately be attributed to random mutation. Each mutation is tested for adaptability to the environment; with adaptive mutations retained for future generations while maladaptive mutations are discarded. While most mutations have negative consequences and so are discarded by the system, occasionally mutations are beneficial and retained for future use. Through this process, random mutation is the ultimate creator of all biological novelty.
2. Mutation is the first step in entrenching the role of creativity in evolution by natural selection. The second step is transmitting information by asexual or sexual reproduction. Asexual reproduction can precisely reproduce a mutation — ensuring its continuation. Sexual reproduction can leverage the effect of previous mutations by mixing the information held in the genomes of male and female ancestors, and providing a step in ensuring the continuation of successful mutations.

3. The third step is providing a degree of control in the frequency and location of mutations. The environment, through the epigenetic system, plays a major role in this step. Depending on the external environment, some mutations are important at certain times or locations. For example, as snakes' prey develop resistance to its poison through mutations, the composition of the poison needs to change to remain effective. Accordingly, mutations in that part of snakes' genomes that control poisons are much more frequent than mutations elsewhere. In this way, snakes' genetic system is influenced by what happens in the external environment with the term 'epigenetic system' used to provide a label for the process. Accordingly, the external environment is critical to evolution by natural selection, and the epigenetic system provides a bridge between the environment and the genetic system.
4. Together, the previous three steps are used to build a genome, which is the fourth step. A genome is the repository of the stored genetic information required by an individual and a species to survive in the natural environment. Each genome is the sum of the myriad of previous mutations retained following repeated reproduction.
5. Lastly, the epigenetic system again comes into play in a different role through the fifth principle. Consider a skin cell and a liver cell. The two cells obviously have very different structures and functions — they have different phenotypes. In isolation, the genetic system cannot explain those phenotypical differences because the genetic information held in the nucleus of a person's liver cells is identical to the genetic information held in the nucleus of the same person's skin cells. Instead, the vast differences in structures and functions of genetically identical cells comes from the environment which directs those differences via the epigenetic system. That system turns some genes off and some genes on; resulting in liver and skin cells with their very different phenotypes.

Together, these five principles provide a natural information processing system capable of explaining the creativity demonstrated by evolution by natural selection. This natural information processing system has created the innumerable, ingenious structures and processes we see in the species and individuals of the biological world. It is self-governing in that it has constructed the immensity of the biological world without direction from a program or 'central executive' to govern its functions, except insofar as the five principles can be considered a program. It differs from a computer that requires a 'central executive' program to run. The same principles apply to human cognition and so also can explain human creativity without recourse to a 'programmer'.

Human Cognitive Architecture

Humans have evolved with two different cognitive systems.[9] The first deals with biologically primary knowledge and the second with biologically secondary knowledge.

Biologically primary knowledge deals with information we have evolved to acquire over many generations. It does not need to be taught because we acquire it easily, automatically and unconsciously. Some of these activities are immensely complex from an information processing perspective but we find them simple because we have evolved to acquire them — as they are critical to our survival. Examples include: learning to listen and speak a native language; learning general problem-solving skills; or learning basic social relations and interactions. Most examples are generic-cognitive skills such as thinking and problem solving that are central to human cognitive activity.

The five natural information processing principles discussed above do not apply to the acquisition of biologically primary information since each principle itself constitutes a biologically primary skill.[10] However, they do apply to the acquisition of **biologically secondary information**, which is information that is culturally important to us but that we have not specifically evolved to acquire. Examples include almost everything taught in schools and other educational establishments. These have been devised precisely to teach biologically secondary information — because without them, such information tends not to be acquired. Ergo, we will learn to listen and speak without schools, but most people did not learn to read and write until the advent of mass education.

Most biologically secondary information is domain specific.[11] For example, while we have evolved to acquire general problem-solving skills because it is difficult for us to survive as humans without them, most people can survive adequately without ever learning the solution to an algebraic problem such *a/b = c, solve for a*. Such biologically secondary, domain-specific knowledge needs to be explicitly taught or it will not be acquired.

The five principles used to describe the information processing characteristics of evolution by natural selection apply equally to the information processing characteristics of human cognition when dealing with biologically secondary, domain-specific knowledge. As is the case for evolution by natural selection, the system is self-governing without the need for a central executive to allow it to function. While the system functions to allow us to process biologically secondary, domain-specific information, each of the five principles constitutes a biologically primary, generic-cognitive skill that does not need to be taught — because we have evolved to acquire it.

How we acquire novel information

Humans can acquire novel, biologically secondary, domain-specific knowledge either during problem solving (covered by the first principle dealing with random mutation in evolutionary biology) — or by obtaining it from other people (covered by the second principle dealing with reproduction in evolutionary biology). Random generate-and-test is at the heart of solving novel problems, just as it is at the heart of random mutation.

Before using random generate-and-test to solve a novel problem, we characteristically will first attempt to relate the problem to familiar problems. When solving a novel problem, we will automatically use previous knowledge as far as possible to arrive at a solution. This generalisation from previous problems does not need to be taught because it is biologically primary. Notwithstanding, assuming it really is a novel problem, at some point we will find that previous knowledge no longer advances us towards the problem solution. At that point, we will have no choice but to randomly generate a move and test it for effectiveness by seeing whether it moves us closer to the problem goal. This random generate-and-test procedure is analogous to random mutation with its test of fitness or adaptivity to the environment.

Random generate-and-test is essential to creativity. There is no known alternative available in the absence of knowledge. As an example, it might be argued that problem-solving by analogy provides an alternative. After all, my current argument is heavily based on the analogy between evolution by natural selection and human cognitive architecture. In fact, the analogy only can be established after it has been made. Before it is made, in the absence of knowledge, the only available procedure is to choose evolution by natural selection as the source analogue and test to see if the analogy works. Other analogues — whether based on a scientific theory from a different domain or based on something entirely different — may be better or worse; but in each case, if knowledge is unavailable to test the effectiveness of the analogy, random generate-and-test is left as the only possible problem-solving procedure.

While random generate-and-test is the ultimate source of all creativity — whether dealing with evolution by natural selection or human cognition — there is a much better, more efficient way of obtaining information: it can be borrowed from elsewhere. During biological reproduction, enormous amounts of information are borrowed from ancestors — a far more efficient process than creating the information in the first instance by random mutation. Similarly, the human cognitive system can borrow domain-specific, biologically secondary information from other people. We have evolved to do so with the skill being biologically primary — that is, we are all capable of learning from instructors in educational settings, and do not need specific instruction to 'learn how to learn'. Our ability to obtain large amounts of information from other people may arguably be a major reason for the dominance of human beings as a species.

Because humans have a unique, evolved ability to obtain information from each other, it follows that students should be presented with novel information — rather than merely being assisted to create it for themselves using the slow, inefficient procedure of random generate-and-test. Presenting information to students makes use of our biologically primary skill of obtaining information from each other. While that information first had to be created using the slow, inefficient process of random generate-and-test, once created, it can be transmitted relatively easily and quickly to others via the second principle.

How we process and store novel information

Once we have obtained novel information, either by generating it ourselves or from others, it needs to be processed. That means aligning the cognitive system with the external environment. The epigenetic system accomplishes the analogous aim for evolution by natural selection by appropriately modifying the number and location of mutations to match the needs imposed by environmental conditions. **Working memory** plays this role in human cognition. Novel information from the environment is transmitted via the senses to working memory for processing in a similar manner to the way the environment determines the nature and number of mutations in a genome.

Working memory has two critical characteristics when processing novel information. No more than 3-4 elements of novel information can be processed at any given time and that information can be held for no more than about 20 seconds without repetition before being lost. These limitations are characteristic of working memory when dealing with novel information and as discussed below, do not apply when working memory deals with familiar information.

Once novel information has been processed by working memory, if it is likely to be useful in the future, it is retained in a **long-term memory** that — unlike working memory — has no known capacity or duration limits. The role of long-term memory in human cognition is analogous to the role of a genome in evolution by natural selection. Both hold enormous amounts of information and both are arguably the central structures in their respective information processing systems. While that statement is likely to be non-controversial with respect to evolution by natural selection, the role of long-term memory in human cognitive architecture tends to be frequently misunderstood.

We sometimes tend to think of long-term memory as being a structure for holding isolated, unrelated snippets of information. That tendency, for example, is reflected in statements such as "I have a terrible memory for names". At any given time, we are conscious only of those contents of long-term memory that we have transferred to working memory. Hence, at any given time, we are conscious only of a tiny fraction of the contents of long-term memory — leading to the assumption that this structure is relatively minor in importance.

In fact, the role of long-term memory is to store enormous numbers of complex, organised codes. Consider the following statement: "The waiter in the restaurant spilled soup on my lap and so did not get a tip." We all understand this simple statement; but to understand it, we need to hold the following information in long-term memory: *Soup is a liquid food. Restaurants serve food with waiters being the serving agents. Laps only exist when we sit down, not when we stand up or lie down. We do not like liquid being spilled on our laps. Waiters derive some of their income from tips. We are less likely to provide a tip when a waiter spills soup on our laps.* Not only do we need to hold this information in long-term memory, we also need to hold information about 'food', 'liquids', 'income', 'tips', the meaning of the word 'spilled', and the basic economic system. Long-term memory must hold all this information for us to be able to understand a simple statement. Our ability to create anything is dependent on vast complexes of knowledge held in long-term memory.

How information held in long-term memory facilitates creative and critical thinking

The previous four principles lead to the last critical principle: information stored in long-term memory can be transferred back to working memory to generate action. The environment plays a critical role in triggering action that is appropriate to the extant circumstances, in the same manner that the environment is critical in determining phenotypes via the epigenetic system in evolution by natural selection. It is notable that while working memory is severely limited when dealing with novel information — as outlined above — it has no known limitations in either capacity or duration when dealing with familiar information transferred from long-term memory. The enormous amount of familiar — as opposed to novel — information that can be easily processed and held in working memory is demonstrated by the 'spilled soup' example.

In this manner, the contents of long-term memory transform and define us in the same way as the contents of a genome define the nature of an organism or a species. Everything we have ever learned is stored in long-term memory; from simple rote-learned facts to enormous complexes of related information. The intricate relations between working and long-term memory determine who we are and what we can do, and assist in defining consciousness. At any given time, we are conscious only of a tiny proportion of the contents of long-term memory. That information, in conjunction with information flowing from our senses, defines consciousness and permits us to engage in creative activity.

The analogy between evolution by natural selection and human cognitive architecture is important because we know evolution by natural selection is an immensely creative system of which we have considerable knowledge and understanding. While the only perfect analogy is between a system and itself, if this analogy holds, it has the potential to throw light on human creativity.

Implications for Educational Theory and Practice

Critical and creative thinking skills in education need to be considered within the confines of natural information processing systems in general, and human cognitive architecture in particular. Yet they are almost never considered within these contexts. It is rare for a discussion of critical and creative thinking skills to incorporate the role of our limited working memory when dealing with novel information, the vast increase in the capacity of that structure when processing previously-stored information transferred from our immeasurably large long-term memory, or our uniquely evolved skill in efficiently obtaining information from other people. The absence of any discussion of human cognitive architecture when considering concepts such as critical and creative thinking provides grounds for scepticism concerning the advocated teaching procedures or suggested attempts at measuring the relevant skills.

Facilitating critical and creative thinking

Educators are increasingly tasked with developing their students' creativity and critical thinking skills — often in a cross-curricular, generic context. The Australian Professional Standards for Teachers require teachers at all levels to demonstrate the use of teaching strategies to develop student's "knowledge, skills, problem solving and critical and creative thinking". According to the OECD's TALIS survey, more than four in five Australian teachers believe they are helping their students to think critically. More than two-thirds of Australian teachers say they frequently, or always, give students tasks that require them to think critically. Across OECD countries, four in five teachers say that teaching creativity and critical thinking is included in their formal education and training.

Despite the emphasis placed on facilitating creativity and critical thinking, it is not clear to educators how to do so. The OECD recommends teachers give students tasks that require them to think critically; asking students to decide on their own procedures for solving complex tasks, presenting tasks for which there isn't an obvious solution, among others. The most common strategy described or implied for the acquisition of critical and creative thinking skills is to have learners discover information for themselves.[12]

The discourse omits the fact that there are no established bodies of evidence based on randomised, controlled trials demonstrating that critical and creative thinking as a generic-cognitive skill is enhanced by having students discover information for themselves. If this approach were successful, years of implementation should have produced numerous studies demonstrating the improved performance of students following the introduction of the preferred procedures — with properly controlled studies indicating when the procedures work, when they do not work, and the best ways of making them work. Instead, we have advocacy for teaching generalised critical and creative thinking skills based only on the valid assumption that no one is going to argue that teaching students critical and creative thinking skills is a bad idea. As happens far too frequently in education, the absence of either a theoretical base or prerequisite data seems not to be a concern.

This lack of supporting evidence is not slowing approaches to supposedly develop creativity and critical thinking in classrooms. In some educational contexts, attempts to facilitate critical thinking include increasing students' awareness of, and supposed ability to mitigate, cognitive biases that may result in illogical reasoning. In particular, it is claimed that generalised, content-independent strategies — such as debiasing and reflection — will sufficiently result in more critical thinkers. However, there is little evidence that such strategies bring any educational benefit. Moreover, they misdiagnose a lack of critical thinking as a deficiency in 'thinking skills', rather than as a deficiency in knowledge.

In any case, the characteristics of human cognitive architecture do not mean we can do nothing to facilitate critical and creative thinking. Rather, they indicate what we can and cannot do.

We certainly can assist learners to acquire a biologically secondary knowledge base in a given domain by providing them with that base. Cognitive load theory indicates how a knowledge base can be efficiently acquired.[13] In turn, that base can facilitate critical and creative thinking. An adequate — and preferably extensive — domain-specific knowledge base is both necessary and, in many cases, sufficient to allow critical thinking to occur. For example, with a relevant knowledge base, we are more likely to easily detect statements that make no sense in light of that knowledge. In the absence of such a knowledge base, it may be difficult or impossible to distinguish between valid and invalid statements.

With adequate domain knowledge, none of us needs training in critical thinking to determine that a statement contradicts that knowledge. So training in critical thinking, whatever its constituents, inevitably will be redundant or, indeed, spurious. Domain-specific knowledge provides us with all the critical thinking skills we need and all we are able to acquire. Of course, domain-specific knowledge will not transfer to unrelated areas, but education researchers have spent over a century searching for, and failing to find evidence of, transfer to unrelated domains by the use of generic-cognitive skills.

Measuring critical and creative thinking

Periodically, there are calls for the inclusion of measures of critical and creative thinking when assessing students. For instance, the OECD promises to measure students' creativity across four domains: written expression; visual expression; social problem solving; and scientific problem solving. Students are advised to engage with open tasks that have no single correct response. They are either asked to provide multiple, distinct responses, or to generate a response that is not conventional.

In addition, there are several popularly used assessments of critical thinking skills. For instance, the California Critical Thinking Skills Test claims to assess — in a 'discipline neutral' way — participants' overall reasoning skills, analysis, interpretation, evaluation, explanation, inference, deduction, and induction. Similarly, the Watson-Glaser Critical Thinking Appraisal (WGCTA) is designed to test general critical thinking processes.

However, all claims to measure creativity and critical thinking, implicitly or explicitly, assume these skills can be taught in educational organisations and institutions. It is further assumed that such teaching will be encouraged by the inclusion of appropriate tests.

Rarely, if ever, are calls to measure critical and creative thinking associated with the previously discussed cognitive architecture. It is this architecture that must give rise to the thinking skills under consideration. We need to clearly understand exactly what it is we are measuring and, equally importantly, what we are not measuring.

Based on human cognitive architecture, a creativity assessment is, in effect, measuring a student's innate ability to use the random generate-and-test engine of creativity that is biologically primary and so unteachable, combined with knowledge that has been stored in long-term memory that is biologically secondary and is eminently teachable. We are not measuring critical and creative thinking strategies that currently remain unidentified.

Consider a student who devises a creative answer to a test item. If it is creative, random generate-and-test will have played a role in that answer. That same answer to the same item is obviously not creative if the student has considered the issue previously and simply uses knowledge held in long-term memory to provide the answer. But without an accurate map of each student's knowledge base, we cannot determine whether an answer to a question is creative. We cannot determine creativity just by considering the nature of the question and its answer. We also need to consider students' knowledge — information that is usually unavailable when dealing with large numbers of students.

The case for optimism regarding creativity and critical thinking in schooling

Notwithstanding the above criticism, there has been some progress. Traditionally, this field has implicitly assumed we could teach critical and creative thinking skills as generic-cognitive concepts so that these skills can then be used in any area or field. It now is realised, at least by some,[14] that we should not expect transfer of these skills between domains, and that the ability to think critically and creatively is restricted to domains in which we are knowledgeable. The recognition that we cannot think critically and creatively in areas in which we do not have extensive knowledge is a welcome development. Knowledge held in long-term memory is the first prerequisite of critical and creative thinking and, as indicated below, the only teachable component.

The realisation that critical thinking is domain-specific rather than general has yet to permeate all curriculum bodies. For example, the New South Wales curriculum based on Australian Curriculum recommendations states: "Critical thinking is also classified as a general capability. This means that it can be developed both across and within different subject domains."[15] This statement ignores everything we know about human cognitive architecture and ignores the fact that there is no body of evidence in support of the hypothesis that critical thinking can be taught as a "general capability". In contrast, it certainly can be taught "within different subject domains" by providing learners with knowledge of the domain stored in long-term memory. That knowledge can indicate the validity of statements relevant to the domain, but is likely to say nothing of the validity of statements from unrelated domains.

The second ground for optimism is that there is now understanding that critical and creative thinking are natural human characteristics. As Ronald Beghetto states, "Creative thinking is something that students already have the capacity to do."[16] Using this paper's terminology, we all engage in critical and creative thinking because it is biologically primary. We need to be constantly aware that, based on our knowledge of human cognitive architecture, the only discernible engine of creativity is random generate-and-test associated with a substantial knowledge base. We can encourage learners to engage in random generate-and-test where it is appropriate,[17] but there is no point attempting to teach the procedure because we have all evolved to use it in the absence of knowledge.

Conclusions

In part fuelled by a motivation to see teaching and learning as about *thinking* rather than *knowledge*, educators and policymakers continue to see creativity and critical thinking as a key function of schools. This paper shows why this motivation needs to reflect the evidence on how students learn, as demonstrated by our knowledge of human cognition.

Here is a test for those who feel the points made in this paper are erroneous and that teachable, learnable, generic-cognitive, critical and creative thinking skills can and should be taught. What generic, critical and creative thinking skills do you use? Which of your creativity strategies do you feel should be taught to students? If you have some candidates, is there any evidence from randomised, controlled trials that teaching these strategies to students improves performance? If the only candidate procedure is to present students with problems that they have difficulty solving or simply cannot solve, then we should at least consider the possibility that teachable, learnable, generic-cognitive, critical and creative thinking skills do not exist.

Does this mean there are no critical and creative thinking skills? There certainly are, but they are all biologically primary because they are too important to be left to the secondary system. Here is the biologically primary set of steps we all use to solve a novel problem: We consider where we are in the solution now, consider the goal of the problem, find differences between where we are now and the goal, find moves that will reduce those differences, and repeat the process until we reach the goal. We all follow these steps unconsciously because we have evolved to solve problems in this way. Teaching people how to use this problem-solving strategy would be a waste of time.

Of course, some students demonstrate more creativity and greater critical thinking skills. These differences are predominantly due to differences in biologically *secondary* knowledge; mainly students' domain-specific knowledge that they have acquired. Put simply, students who have sufficient knowledge in a particular area will face less burden with the cognitive processes of creativity and critical thinking than those who lack knowledge, and thus must also search for relevant information.

We know that the random generate-and-test process provides the ultimate creativity engine in nature. We also know that it is the creativity engine in human problem-solving and that it is biologically primary and unteachable. If critical and creative thinking is to be taught in educational establishments, an alternative creativity engine to random generate-and-test needs to be specified and tested for effectiveness. Until then, there is no justification for advocating the inclusion of general critical and creative thinking in curricula.

Of course, it needs to be emphasised that just because we have not found any teachable, general, critical and creative thinking skills does not mean that they do not exist. But until a theoretical framework with empirical supporting results appears, advocating for the introduction of critical and creative thinking skills in educational contexts is premature.

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John Sweller is an educational psychologist and Emeritus Professor at the University of New South Wales. He is best known for formulating cognitive load theory, which uses our knowledge of evolutionary psychology and human cognitive architecture as a base for instructional design. The theory is one of the most highly-cited educational psychology theories. John has authored over 200 academic publications and is a Fellow of the Academy of Social Sciences in Australia.

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