The secrets of mindful STEM teaching and learning

A L White1,2
1University of Western Sydney, Australia
2SEAQiS, Yogyakarta, Indonesia

E-mail: allan.white6@gmail.com

Abstract. The pressure upon a Science, Technology, Engineering or Mathematics (STEM) educators has increased as the demand for workers with STEM capabilities develops while worldwide the number of students electing to specialise in STEM areas is declining. In 2018, the Indonesian Ministry of Industry (KPRI) released a document titled ‘Making Indonesia 4.0’, stating STEM teachers will be expected to produce students who have several “careers” during their working lives and have the skills needed which includes technical capabilities, creativity and innovative problem-solving. This will occur in a context where the future of work remains human and so while the new technologies have the capacity to automate many tasks, they also create as many jobs as they replace. As well as these governmental expectations, STEM educators are being continually confronted with an avalanche of advice on the best ways of teaching and learning their subject. This advice comes from across the spectrum of expertise that includes parents, outstanding teacher heroes, commercial interests, and dubious ‘experts’ who have no pedagogical knowledge or experience. This paper will attempt to cut through this avalanche and dig down to the bedrock of successful and sustainable STEM teaching and learning. While this paper is written for all STEM educators, it will tend to favour examples from the mathematics and brain research disciplines.

1. Introduction

Who would want to be a Science, Technology, Engineering or Mathematics (STEM) teacher today? The pressure upon these educators has escalated and continues to increase as the demand for workers with STEM capabilities grows at a time when the number of students electing to specialise in STEM areas is declining. Consider the following evidence.

In 2018 the Indonesian Ministry of Industry (KPRI) released a document ‘Making Indonesia 4.0’ as a response to the Fourth Industrial Revolution (4IR) that involves the introduction of cyber physical systems into existing Indonesian systems [1]. At the 2018 Education World Forum, the Indonesian Minister for Research, Technology and Higher Education, HE Prof Mohamad Nasir, elaborated upon this document stating that the schooling and tertiary systems will be expected to deliver students who have the skills needed by 4IR, which includes technical capabilities, creativity and innovative problem-solving. STEM educators will be expected to produce students who will have several “careers” during their working lives rather than just one, and are motivated to participate in adult training and lifelong learning. Schools and tertiary institutions will be expected to embrace online education and access education across borders, credit transfer and professional networks [2].

Countries around the world are also struggling with these issues. A recent report by Deloitte [3] upon the Australian context stated that the future of work is human and while the new technologies have the capacity to automate many tasks, they also create as many jobs as they replace. Employment
is growing in areas that are hardest to automate. People with their unique interpersonal and creative skills will be central to the future of work. For every problem arising from 4IR there are employment opportunities, and the world isn’t running out of problems. While jobs are increasingly likely to require cognitive skills of the head rather than the manual skills of the hands, they also increasingly need workers who can use their hearts (known as soft skills) in the interpersonal and creative roles that require uniquely human skills like creativity, customer service, care for others, and collaboration. Thus there is a move towards including the importance of Arts disciplines in the mix and agitating for STEAM. The demands and pressures upon current STEM teachers and lecturers to deliver students with these capabilities and expectations are enormous.

As well as the political and economic pressures, all STEM teachers are continually confronted with an avalanche of advice on the teaching and learning of their subject by voices across the spectrum of expertise that includes: parents suffering from ‘STEM trauma’ as a result of their school experiences; or experts of the STEM content but who are ignorant of the secrets of good teaching and learning; or commercial interests who design wonderful marketing campaigns promoting products based on dubious or destructive teaching and learning practices; or the subject ‘teacher heroes’ who produce wonderful student learning outcomes. In the last case, the secrets that underlie the success of the ‘teacher heroes’ are often hidden from sight under the brilliance of the teacher’s personality and enthusiasm. Teachers need convincing that they too can produce outstanding learning outcomes by adopting the pedagogical strategies of the ‘teacher heroes’ rather than trying to adopt their personality. The fact that STEM teachers and lecturers continue to work in schools and universities, and strive to do their best for their students is why I regard them as national treasures and I have written elsewhere that I regard them as super heroes [4].

This paper will attempt to cut through this avalanche and dig down to the bedrock of successful and sustainable STEM teaching and learning. It will depersonalise the aura around the subject ‘teacher heroes’ to assist teachers to avoid attempting to be clones of the ‘teacher heroes’ and by encouraging them to be themselves and to do what these ‘teacher heroes’ do in the classroom. It will outline the teaching and learning practices that produce the wonderful student achievement outcomes while promoting positive attitudes towards STEM subjects and careers.

In the next sections I want to examine the nature of STEM learning. Thus the first section argues that learning is essentially a struggle by the brain to make sense of what it is experiencing. Students who are told that learning is “always” fun and easy are being misled. When they are challenged they give up because they find it too hard and not fun. I have heard students say: “this is not easy so I am just not a mathematics person”. Students need to accept that learning is a process that requires struggle and be made aware of research that shows the brain improves and grows through concentration, struggle and challenge [5-8].

The very best mathematicians wallow in the enjoyment of struggling with mathematical ideas and this should be among the aims of math teachers – to help students enjoy the struggle of mathematics [8].

On the other hand playtime or having fun with STEM should not be dismissed as a frivolous activity; something that students do to give them a break from the arduous slog of ‘legitimate’ learning. What is needed is a balance of both where having fun and struggling to learn are seen as partners and essential characteristics of the productive classroom. So what must teachers do to create this environment of enjoyable and productive struggle?

2. Learning is a struggle
To have students enjoy struggling with problems involves developing their attitudes towards their learning. The STEM curriculum includes many facts, skills, procedures and concepts and STEM teachers are expected to teach their mandated curriculum while inculcating positive attitudes in their students towards the subject while engaging and motivating them. The messages that STEM students
receive from significant others such as parents, teachers, friends and so on, has a large effect upon their attitudes towards STEM subjects and their achievement. There has been considerable research completed in this area.

For example psychologist Dweck [9] and her research team collected data over a number of years and determined that everyone held a core belief about their learning and their brain. The researchers made a distinction between what they labelled as a fixed mindset and a growth mindset. Someone with a fixed mindset believes that while they can learn things, they cannot change their intelligence level. Whereas someone with a growth mindset believes that the brain can be changed through hard work and struggle; the more a person struggles the smarter they become. Studies have shown that the performance of students with a growth mindset outstrips those students with a fixed mindset [7].

Learning as a struggle resonates with educators who have long known that students who experience ‘cognitive conflict’ learn more deeply and that struggling with a new idea or concept is very productive for learning [10]. The seventh of eight high-leverage teaching practices resulting in the NCTM [11] publication encourages educators to ‘support productive struggle in learning mathematics’. Doidge [12] cited the work of Moser and colleagues in 2007, which showed that when students make mistakes in mathematics, brain activity happens that does not happen when students get the work correct.

While successful STEM teachers try to make their learning joyful, interesting and fun, they also encourage their students to struggle with learning challenges. There is a need to socialise the message and one Australian teacher who embraced this challenge has his class regularly exclaim ‘give me more, my brain feels no pain, this is good for me’ and ‘when the going gets tough, the tough get going’. In this playful way he uses sporting metaphors to encourage his students when challenged to persevere. The class also regularly celebrates success and achieving personal milestones in a happy and fun way using sporting themes. A Coke can nailed to a piece of wood was the ‘World Cup of Courage’, presented weekly to the best ‘strugglers’. If you go to a gym to get fit and you have sore muscles afterwards, you don’t say: ‘I’m not a gym person’ and give up. You know that the process of getting fit involves challenge, struggle and a little pain in order to achieve the desired outcome.

Boaler [7] provides a wealth of research evidence involving mathematics learning that supports Dweck’s work on mindsets.

It turns out that even believing you are smart - one of the fixed mindset messages - is damaging, as students with this fixed mindset are less willing to try more challenging work or subjects because they are afraid of slipping up and no longer being seen as smart. Students with a growth mindset take on hard work, and they view mistakes as a challenge and motivation to do more [7].

As a consequence, teachers giving feedback to students should target the specific behaviours or outcomes and not give an evaluation of the intelligence or personality of the student. Statements like: “I am really proud of how hard you have worked” or “good thinking” are more constructive than “you are so clever” or “you are a smart girl” or “you are a naughty boy”. The target of all feedback should be towards the struggle, the perseverance, the determination and the quality of the outcomes.

The way teachers deal with student mistakes also has an influence upon attitudes. Scaffolding first introduced in the late 1950s by Jerome Bruner refers to the support given by the teacher during the learning process which is tailored to the needs of the student with the intention of helping the student to achieve certain learning goals. It aims to support the student to face and overcome challenges through struggle. Scaffolding allows students to make mistakes and to learn from their mistakes in order to overcome their challenge. Thus mistakes become learning opportunities. Boaler [6] argued that brain research demonstrated that when students struggle and make mistakes, synapses fire and their brain grows. Scaffolding should assist the learning process to promote a deeper level of learning and the amount of scaffolding given by the teacher varies according to each individual student. It should never become a cognitive emptying process whereby the cognitive challenge of the task is removed and turned into a series of relatively simple questions [13]. In fact the constant use of short
closed questions in the mathematics classroom that students get either right or wrong transmits fixed messages to students that mathematics is a subject that you can either do or not. The enemy of understanding is teaching the steps to solving a problem because then the students do not have to think about what they are doing. Teaching students which buttons to push in a Google™ search is useless if students do not know how to interpret the answer. If teachers are to develop growth mindsets then they need to open up mathematics questions so there is space inside them for learning.

The normal sense of the word scaffold implies an outside support structure for a process of building. In the next section there is a brief discussion of other internal and external structures involved in the learning of mathematics.

3. Learning involves structure
In this section, a brief discussion will be presented of a model of the internal structure of the brain and the structure of the discipline of mathematics and their importance to purposeful and productive mathematical achievement.

The most complex structure in humans is the brain which has over 1 billion neurons and any neuron can communicate with up to 10,000 others. The neurons in the brain continually fire in parallel as the brain works through the huge input of information by simply discarding irrelevant data and focusing only on a few important aspects at any given time. The myth that some children are born with a mathematics brain, while the majority of students miss out, has been largely discredited with research showing that genetics has a minor part while experience provides the major contribution towards mathematical ability [5,7,12]

... scientists now know that any brain differences present at birth are eclipsed by the learning experiences we have from birth onward [7].

Children are not born knowing mathematics but are born with the ability to see patterns which facilitates both language and mathematics. They are born with the potential to learn mathematics. How this potential is nurtured, encouraged, and challenged is the responsibility of parents and teachers. Consider the following evidence. Brain and mathematics educational research into why young Chinese children have better early mathematical abilities than other non-Chinese children has highlighted the part played by the Chinese number system and early educational experiences.

The brain regions around the intraparietal sulcus have been shown to be critical for mathematical processing... The brain regions for mathematical processing may have increased or decreased neural activities, and may even change in neural structure, as a result of long-term practice under some context of culture, language, and education [14].

When a student has a new experience, an electric signal sparks, cutting across synapses and connecting different parts of the brain and forms networks of neurons that fire together. If the child is repeatedly exposed to this new experience, then either the synaptic activity creates lasting connections in the child’s brain (long-term memory), or shallow learning (temporary memory such as in the immediate memory or the working memory) that quickly decays or is discarded. Sousa [15] stated that scientists currently believe these two types of memory are where the brain stores information for a limited time. The immediate memory and it is where the brain stores information briefly until the learner’s brain decides what to do with it and remains here for about 30 seconds after which it is discarded as unimportant. The working memory stores information for 10 to 20 minutes usually but sometimes longer as it is being processed. The basis of whether new information is transferred from the immediate to the working memory relies on the brain deciding that the information is either relevant or meaningful to the student. Note that relevance is influenced by beliefs such as the student’s mindset.

Information stored in the working memory is called shallow learning or sometimes called surface learning. However, recently surface learning has been defined by researchers in a way that is different
to shallow learning [8,16]. Using his *Visible Learning* database involving more than 1200 meta-analyses, over 70,000 studies and over 300 million students, Hattie [16] reported that effective teaching practices involved three phases of learning, namely surface, deep and transfer learning. Surface learning was defined as

... the phase in which students build initial conceptual understanding of a mathematical idea and learn related vocabulary and procedural skills [8].

Deep learning for John Hattie and colleagues is when students consolidate their understanding and apply and extend some part of surface learning knowledge to develop deeper conceptual understanding. Transfer learning is exhibited in students taking their consolidated knowledge and skills and applying it to new challenges and contexts. It is transfer learning that is demanded in the document ‘Making Indonesia 4.0’ as a contributor to Indonesian development and change.

Hattie [8] noted that pure discovery learning is too time inefficient in the school classroom and students need someone to help them develop an understanding of the conceptual structure of mathematics. In a classroom environment of enjoyable and productive struggle, when students are persevering with a problem they are provided access to the underlying structure by the teacher.

So STEM teachers facilitate within their students a progressive process of building up the complex structure and interconnections of mathematics as the students’ brains build a complex neural structure. This progressive process will be briefly discussed in the next section.

4. Learning is a progressive process of understanding

The development of teaching has produced a large range of strategies where some are good for student learning and achievement and some are bad [4,17]. The problem facing teachers and educational experts when making a choice from research studies is that a specific strategy with a very large sample size while statistically significant can have little impact or value in the classroom. Hattie and his colleagues’ work has provided an instrument they call a ‘barometer’ that allows teachers and researchers to ignore weak practices even when they are statistically significant.

John (Hattie) was able to demonstrate that influences, strategies, actions and so on with an effect size greater than 0.40 allow students to learn at an appropriate rate, meaning a year of growth for a year in school [8].

This pictorial barometer examined various strategies from many research studies to inform teachers’ choice [8]. The good strategies (0.4 and above) helped students to understand, construct meaning and to connect with their prior learning and with the conceptual structure of mathematics. The process of constructing meaning is important because it determines whether that information will be learnt and retained in the brain. Understanding, making sense, or making meaning is a crucial consideration of the learner’s brain in moving information to both the working and long-term memory.

Students may diligently follow the teacher’s instructions to memorize facts or perform a sequence of tasks repeatedly, and may even get the correct answers. But if they have not found meaning by the end of the learning episode, there is little likelihood of long-term storage [15].

Making sense, meaning or understanding is a process that assists deeper learning and is essentially a process of an increasing accumulation of stimulation and connection. Skemp [18,19,20,21,22,23] proposed the terms instrumental and relational understanding to illuminate classroom teaching where instrumental mathematical understanding is described as ‘rules without reasons’ or knowing how or what to do to get an answer, whereas relational understanding is concerned with meaning and knowing how and what to do with the added knowledge of why it is being done to get an answer. Skemp [18,19] discusses the development of schemas as evidence of the construction of relational
understanding and this resonates very strongly with the structure of the neural connections within the brain and with the research literature on ‘connected knowledge’. To transfer from the working memory to the long-term memory, the brain requires the new information to be both relevant AND meaningful. This transfer involves more brain processing which results in greater neural connections and the formation of networks that are integrated (connected knowledge). However, in the process of developing deeper learning, both instrumental and relational understanding are needed. A model attempting to demonstrate this interplay of instrumental and relational understanding is called: The scale of teaching for understanding, and has been discussed more fully elsewhere [24].

In the process of deepening understanding a process of ‘Deliberate Practice’ is needed. It is not merely a process of repetition of the same type of question. It is a process of practice with questions that increase in complexity and challenge and seek to broaden understanding while introducing more connections with the conceptual structure of mathematics.

As learning becomes deeper it involves compression. Language is a good example of compression where a single word can stand for a whole complex of interlinked ideas. It is argued that mathematical abstraction is a natural process of mental compression where complicated phenomena are compressed into thinkable concepts [25].

Mathematics is amazingly compressible:-you may struggle a long time, step by step, to work through the same process or idea from several approaches. But once you really understand it and have the mental perspective to see it as a whole, there is often a tremendous mental compression. You can file it away, recall it quickly and completely when you need it, and use it as just one step in some other mental process. The insight that goes with this compression is one of the real joys of mathematics [26].

Thus the process of building understanding leads to insight. An insight appears to result from a connective process within the brain or a quick and efficient restructuring that produces new understanding which is a compression of the original connected information. Compression or automatic responses are not the result of rote learning. Rote learning relies only on memory and is mostly stored and forgotten in the working memory, whereas an automatic response is built upon compressed understanding within the brain. For example, an adult asked to multiply 8 and 7 will generally answer automatically. However when asked to prove the result, the adult would use the networks that were developed at an earlier age (such as repeated addition of seven lots of eight). Generally, due to a more connected understanding of the structure of mathematics, the adult can provide a variety of proofs. Thus the automatic response was not reliant upon memory but upon an underlying conceptual structure. It is the unconscious mind seeking to make the brain more efficient that is behind the process of compression.

Perhaps the most fundamental, and initially the most startling, result in cognitive science is that most of our thought is unconscious that is, fundamentally inaccessible to our direct, conscious introspection. Most everyday thinking occurs too fast and at too low a level in the mind to be thus accessible. Most cognition happens backstage. That includes mathematical cognition [27].

An insight is not an end in itself but can contribute to further understanding and further insight. It is the accumulation of insights that also leads to the compression of mathematical understanding. This compression provides the mathematical tools to efficiently tackle more sophisticated and complicated mathematical problems. The more a student uses the brain networks, the more developed they become, until eventually they become automatic. If certain networks are not used then they decay and eventually disappear. This key ability of the brain to grow and decay has been termed ‘brain plasticity’ or ‘neuroplasticity’.
Returning briefly to the issue of language and compression, as language (like mathematics) is regarded as a code for transferring a thought from one brain to another. People who are fluent in approximately fifty languages are called super linguists or polyglots (from the Greek meaning many tongues – see https://www.bbc.co.uk/sounds/play/w3csz4pt). The Massachusetts Institute of Technology (MIT) Department of Brain and Cognitive Sciences has been using functional magnetic resonance imagery to measure blood flows in the brain to research how human minds create languages and are attempting to detect differences in the brains of polyglots. The regions for language are selective for language and not active for other activities such as arithmetic. Contrary to expectations, polyglots have language regions that appear to be smaller than other humans. As the brain compresses understanding into more efficient networks it does not have to use as much brain tissue in the process. Thus the challenge for schools and universities is to produce student learning outcomes that are built upon a basis of compressed understanding rather than rote memorisation.

5. Conclusion
If the Indonesian schooling system is going to meet the challenges of the Fourth Industrial Revolution and realise the goals of the government contained in the document ‘Making Indonesia 4.0’ then teachers need to be supported through education and training. Educational and brain research can contribute to this support process. This paper has briefly highlighted the complexity faced by current STEM teachers and lecturers who are expected to remain at the forefront of change and deal with the consequences of this change. The Indonesian 4IR plan will fail without good teachers and lecturers. They need support, encouragement, resources and professional development. Rather than being critical of their efforts, they should be valued and regarded as national treasures or as super heroes and foundation workers for the country.

This paper has also sought to discuss some of the findings that brain research has provided to the teaching and learning of STEM disciplines, especially mathematics. Quality research is needed by teachers and lecturers if they are to produce quality results. The paper seeks to motivate STEM teachers and lecturers to rethink some of their strategies so that they continually encourage students to accept challenge, to build their mathematical understanding, to develop links and connections within their knowledge, and to develop positive attitudes towards their learning and knowledge. In mathematics it means that pedagogies involving such types as Problem Solving, Realistic Mathematics, Mathematical Modelling, Mathematical investigations, and others must become part of the everyday strategies of teachers. Investment in teacher professional learning is an investment in the future.

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