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Title:
Translating neuroscience and psychology into education: Towards a conceptual model for the Science of Learning

Date:
2019

Persistent Link:
https://hdl.handle.net/11343/241453

Translating Neuroscience and Psychology into Education: Towards a Conceptual Model for the Science of Learning

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Submitted in total fulfilment of the requirements for the degree of Doctor of Philosophy.

13th July, 2020.

The Science of Learning Research Centre

Melbourne Graduate School of Education

The University of Melbourne

Printed on archival quality paper

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Abstract

In the last 25 years, there has been a dramatic rise in interest in the neurosciences, particularly in the relationship between neuroscience and education. This has resulted in a plethora of claims and promises about how the emerging field of educational neuroscience might revolutionise education, and how knowledge of the brain can enhance - and perhaps is even essential for - effective teaching and learning. In comparison, educational psychology has had a long and distinguished history of direct, substantial impact on educational practice. Both of these disciplines rely on valid translation of their research into educational practice. The purpose of this thesis is to evaluate and empirically compare the respective impact of each of these disciplines, and in the light of that analysis, propose an integrated conceptual model for the emerging field of the Science of Learning that subsumes both educational psychology and neuroscience.

The first step to that end is the proposal of a conceptual *framework* for the Science of Learning. By dividing educational phenomena into five discrete layers (physical, cellular, organellular, individual and sociocultural), this framework simplifies and clarifies the distinctions between the various learning-related disciplines, and their relationships with each other, in accordance with their levels of complexity. A translation *schema* is also proposed, in which four types of valid translation – functional, diagnostic, conceptual and prescriptive – are described. These two artefacts are used to conduct a systematic review of 548 studies in the educational neuroscience literature. This study found, as predicted, that despite many claims, promises and optimism, there was not a single study that *prescriptively* informed educational practices – that is, no study provided a prescriptive application of neuroscience whereby teaching or learning was specifically enhanced.

To compare this impact with that of Educational Psychology, the thesis reports on two empirical reviews of the educational psychology literature around learning strategies. The first review, a meta-analysis of 10 learning strategies, found that educational psychology has enjoyed a long history of profound, direct impact on educational practice. Drawing on evidence from over 50 years of published evidence, this analysis revealed that these 10 learning strategies were robust and substantial in their impact on learning and teaching. A limitation of this research is that the studies focused on a narrow conceptualisation of human learning – predominantly surface level academic achievement.

Building on this, a second review was conducted, this time a meta-synthesis of over 42 learning strategies. The findings of this synthesis reflected those of the meta-analysis, in that there was a robust and substantial evidence base for all 42 strategies, largely derived from psychological research. The more important finding was that a range of moderators was also examined, revealing that certain strategies were more effective at different stages of the learning and teaching process. This broader conceptualisation of learning informed the proposal of a Model for Learning, in which two phases of learning (acquisition and consolidation phases), and three types of learning (surface, deep and transfer) were explicated.

The respective strengths and limitations of both educational psychology and educational neuroscience, as demonstrated by these analyses, informed the proposal of an integrated conceptual model for human learning – the Pedagogical Primes Model for the Science of Learning. This model subsumes and integrates all learning-related scientific disciplines and situates them in accordance with the translation framework proposed in the beginning of the thesis. It is proposed that this model, when used with the translation schema, provides a means by which all learning-related disciplines (including but not limited to neuroscience) can meaningfully communicate with each other, and in so doing enhance the valid translation of Science of Learning research into educational practice.

Declaration

This is to certify that:

- The thesis comprises only my original work towards the PhD except where indicated in the Preface;
- Due acknowledgement has been made in the text to all other material used;
- The thesis contains fewer than 100,000 words, exclusive of tables, maps, bibliographies and appendices.

Gregory M. Donoghue

13th July, 2020

Preface

This thesis is comprised of my own original work. I have conceptualised, researched, and undertaken the data collection, statistical analyses and conclusions. My supervisory team and colleagues provided feedback, commentary and advice, and in the cases of published articles, journal editors mandated various changes to manuscripts in accordance with their publication guidelines.

Publications integral to this thesis (Chapters shown in brackets) and contribution of co-authors

Chapter 2

Donoghue, G. M., & Horvath, J. C. (2016). Translating neuroscience, psychology and education: An abstracted conceptual framework for the learning sciences. *Cogent Education*, *3*(1), 1267422. (CHAPTER 2)

The candidate is the lead and primary author of this article, and the contributions of each author are outlined in the following table.

Chapter 2. Translating neuroscience, psychology and education. An abstracted conceptual framework for the learning sciences						
Author	*Planning %*	*Lit Review %*	*Design of Conceptual Framework %*	*Writing %*	*GR Supervision %*	*Mean %*
Donoghue	80	75	85	80	N/A	80
Horvath	20	25	15	20	N/A	20

Chapter 3

Horvath, J. C., & **Donoghue, G. M.** (2016). A bridge too far–revisited: reframing Bruer's neuroeducation argument for modern science of learning practitioners. *Frontiers in psychology, 7,* 377. (CHAPTER 3)

As the conceptual framework of this paper was primarily designed by the co-author, he retained lead authorship of the published article. In contrast, the candidate undertook the majority of the planning, review and writing of the article, so retains primary authorship. The contributions of each author are outlined in the following table.

Chapter 3. A bridge too far–revisited: reframing Bruer's neuroeducation argument for modern science of learning practitioners						
Author	*Planning %*	*Lit Review %*	*Design of Conceptual Framework %*	*Writing %*	*GR Supervision %*	*Mean %*
Donoghue	60	70	40	70	NA	60
Horvath	40	30	60	30	NA	40

Chapter 4

Donoghue, G.M., & Hattie, J. (under review)..Systematic Review of the Neuroscience Literature, Submitted for publication to Mind, Brain and Education on 29th August, 2019..(CHAPTER 4)

The candidate is the primary and lead author of this article, and the contributions of each author are outlined in the following table.

Chapter 4. Systematic review of the educational neuroscience literature						
Author	*Planning %*	*Lit Review %*	*Design of Conceptual Framework %*	*Writing %*	*GR Supervision %*	*Mean %*
Donoghue	90	90	90	90	0	90
Hattie	10	10	10	10	100	10

Chapter 5

Donoghue, G.M., & Hattie, J.A.C. (under review). *Learning strategies: A meta-analysis of Dunlosky et al. (2013).* Submitted for publication to Contemporary Educational Psychology on 1st September, 2019. (CHAPTER 5)

The candidate is the primary and lead author of this article, and the contributions of each author are outlined in the following table.

Chapter 5. Learning Strategies: A Meta-analysis of Dunlosky et al. (2013)						
Author	*Planning %*	*Lit Review %*	*Design of Conceptual Framework %*	*Writing %*	*GR Supervision %*	*Mean %*
Donoghue	70	90	70	90	0#	80
Hattie	30	10	30	10	100#	20

Not included in calculation of Mean.

Chapter 6

Hattie, J. A. C., & **Donoghue, G. M.** (2016). Learning strategies: A synthesis and conceptual model. *Nature, Science of Learning*, *1*, 16013. (CHAPTER 6)

As the conceptual framework of this paper was primarily designed by the co-author, he retained lead authorship of the published article. In contrast, the candidate undertook the majority of the planning, review and writing of the article, so retains primary authorship. The contributions of each author are outlined in the following table.

Chapter 6. Learning Strategies: A Meta-synthesis and Conceptual Model						
Author	*Planning %*	*Lit Review %*	*Design of Conceptual Framework %*	*Writing %*	*GR Supervision %*	*Mean %*
Donoghue	65	70	40	65	0#	60
Hattie	35	30	60	35	100#	40

Not included in calculation of Mean.

Additional publications relevant but not integral to this thesis (Appendix No. in brackets)

Donoghue, G.M. (2019). The brain in the classroom: The mindless appeal of neuroeducation. In R. Amir, & R.T. Thibault (Eds.), *Casting Light on the Dark Side of Brain Imaging* (pp. 37-40). London: Academic Press. (APPENDIX 5)

Donoghue, G.M. (2017). *The pedagogical primes model for the science of learning*. Poster Presentation, International Science of Learning Conference, Brisbane, 2017. (APPENDIX 1)

Donoghue, G.M., Horvath, J.C., & Lodge, J.M. (2019). Translation, technology & teaching: A conceptual framework for translation and application. In J.M. Lodge, J.C. Horvath, & L. Corrin (Eds.), *Learning Analytics in the Classroom.* London: Routledge. (APPENDIX 6)

Hattie, J.A.C., & **Donoghue, G.M.** (2018). A model of learning: Optimizing the effectiveness of learning strategies. In K. Illeris (Ed.), *Contemporary Theories of Learning.* London: Routledge. (APPENDIX 7)

Horvath, J.C., Lodge, J.M., Hattie, J. A. C., & **Donoghue, G.M.** (2019). The potential irrelevance of neuromyths to teacher effectiveness: Comparing neuro-literacy levels amongst award-winning and non-award winning teachers. *Frontiers in Psychology, 9, 1666*..(APPENDIX 8)

As some of the above publications were published in non-APA standard journals, some editorial changes have been made to ensure a consistent format throughout the thesis.

Funding

In this thesis, as in all of the articles discussed above, acknowledgement is made of the funding provided by the Science of Learning Research Centre, Melbourne Graduate School of Education, under the auspices of which this thesis was completed. The Science of Learning Research Centre a Special Research Initiative of the Australian Research Council. Project Number SR120300015.

Acknowledgements

It is fitting that I acknowledge and thank those people who made this thesis possible. After spending over a decade in child abuse policing and another long stint in children's wellbeing and child protection, I made a tentative return to academic study to better understand children's wellbeing. I had the privilege of completing a Masters at the University of Melbourne, where I had previously completed my under- and post-graduate studies. The education I have received at this university has been life-changing. It was an even bigger privilege to then be accepted by that university to complete this PhD, and for that I have Laureate Professor John Hattie to thank. John was able to see through my rough edges, unexamined hypotheses and Irish stubbornness, and not once lost faith in my project, despite my wavering confidence. Had he not done so, this PhD thesis would not exist, and I owe John an incalculable and heartfelt debt of gratitude – one which I hope to pay forward with what is left of my academic and professional career.

Similarly, Associate Professor Robert Hester very generously agreed to co-supervise the thesis, despite its author having little background in neuroscience. His patience, humility and clarity, coupled with his unique intellect and subject knowledge made my foray into this field both possible and pleasurable. Associate Professor Lawrie Drysdale accepted the position of committee chair, and has always made himself available to check in on my progress. I thank them both.

Family

My family – Joanna, Adrienne, Jake and Brydie – even Patch (R.I.P.) and Peach – endured over 4 years of a time-poor, crusty, often cranky would-be academic. Thank you all for your patience, understanding and support, and I hope this models for you just how important, how life-changing, learning and education can be. I intend to make those challenging years worth the effort for you all.

Tatiana, you arrived at the tail-end of my studies, and your belief in me, your unique way of thinking and your selfless, kind and loving support helped me get over the line. For you, (and Dexter and Luna's presence while I wrote) I am both very fortunate and forever grateful. Thank you.

Colleagues

To all of my colleagues at the MGSE and the Science of Learning Research Centre - particularly, Associate Prof. Jason Lodge, Dr. Dan Cloney, Dr. Elisabeth

Betz, Dr. Jared Horvath, Kellie Picker, and Dr Amy Berry. To you all I express my deep gratitude for the long conversations, challenges, constructive arguments, endless support and your unfading contributions to your own fields. Thanks also to Professor Steven Petrou for his early encouragement to pursue a Ph.D and support throughout. Human learning really is a collaborative, social phenomenon, and we are all the better for it.

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Chapter 1.

Introduction

“Psychology itself is dead.”
Gazzaniga (1998, p. xi).

While renowned neuroscientist Michael Gazzaniga may have over-stated his case in this quote, it is certainly true that across many professions, psychology is losing favour to the newer, more ‘seductively alluring’ (Weisberg et al., 2008) discipline of neuroscience. According to its Latin origins, neuroscience is the study of *nerves*, those bundles of fibres that permeate the chordate body and that communicate between muscles, glands, organs and other cells to enhance biological fitness (see Geary, 1998). Etymylogically, it is very similar to the word psychology, literally the study of the mind, hence it differs from neuroscience in one important (largely philosophical) point: that the immaterial ‘mind’ is a distinct phenomenon from the material ‘nerve’ (or brain). This is the essential foundation of the ‘hard question’ in philosophy (see Chalmers, 2007), a long-standing conundrum in philosophy that remains unresolved. More relevant to education however, is the question of how findings from neuroscience and psychology, mindful of their important differences, can be validly and meaningfully translated into educational theory, policy and practice. Comparing the effectiveness of the translation of these two fields is the subject of this thesis.

Educational Psychology’s Long History

The contribution of psychology to education has been, over many decades, significant to say the least. Educational psychology has a long history and has shed light on many well-accepted learning and teaching phenomena in broad use around the world. The breadth and depth of this contribution is perhaps best indicated by the sample sizes of

Hattie's (2009) meta-analyses: millions of students, hundreds of thousands studies, identifying hundreds of measurable effects. This research is primarily founded in behavioural and cognitive psychology conducted in psychology laboratories, along with some direct educational research involving students in ecologically valid classrooms. Dunlosky et al.'s (2013) comprehensive review of learning strategies reveals a similar story – a long and comprehensive impact of psychological (largely behavioural) research that is directly applied to classroom pedagogy.

This research, however, while of immense and directly practical relevance to formal education, is based on *proximal* rather than *distal* or *ultimate* theories or hypotheses (see Grene, Grene & Depew, 2004; Thornhill & Palmer, 2001). Such proximal theories largely centred around what educational interventions could produce in terms of (often implicit) learning outcomes, and as will be shown in this thesis, such research has become increasingly focused on academic outcomes of learning. However, human learning, when conceptualised through a more *distal* or *ultimate* theory, incorporates a far broader range of phenomena than merely academic achievement. One such ultimate theory is evolution by natural selection.

The Emergence of Evolutionary Educational Psychology

In the most recent development in educational psychology – evolutionary educational psychology pioneered largely by David Geary (Geary, 1998, 2005, 2007, 2009) – education was positioned in its biological context and linked to the ultimate theory of evolutionary biology. Darwin and Wallace's theory of evolution by natural selection (Darwin 1872; Darwin & Wallace, 1858) has become known as biology's 'theory of everything' as, according to Dobzhansky (2013), 'nothing makes sense in biology except in the light of evolution'. Geary subsumed educational practice into this ultimate theory by describing the primary 'purpose' of human learning as affording an evolutionary advantage to the individual in terms of survival or reproductive success, a principal applied to a broad range of other disciplines (see Cosmides & Tooby, 1987; Dawkins, 1976 & 2016; Tooby & Cosmides, 2005).

The principle of natural selection, discovered independently by both Darwin and Wallace dictates that random changes in the breeding of individuals creates biological diversity, and some of those changes are adaptive, and others are not. An adaptive change is one that enables the organism to survive longer and create more offspring – these new traits were heritable, which meant that the offspring also carried those traits, and so they were passed on to subsequent generations. Those changes that did not enhance the survivability and reproductive success of the individual led to the death of the organisms, and so the traits were not passed on to the next generation. This produces selective pressure on certain adaptive traits, and negative pressure against maladaptive traits.

Human learning, seen through this lens, is purposeful, yet not teleological. It is a complex biological phenomenon that is ultimately physical according to a reductionist, materialist epistemology (see Palghat, Horvath & Lodge, 2017). The ability of an individual to learn allowed for the possibility of real-time adaptation to changing external environmental circumstances – and thereby enhancing the individuals' survival and reproductive chances in ways that could not apply to non-cognitive species. Human learning, seen through this ultimate theoretical lens, can be applied to an almost limitless array of interactions with the environmental, biological and interpersonal domains.

That human learning is instantiated in neurology is axiomatic in the biological sciences (see Emes & Grant, 2012, and Gazzaniga, 2004 or Kandel, Schwartz & Jessell, 2000 for an overview). The individual experiences events in the internal (physiological) and external (environmental) worlds, and receives information about those experiences through a range of internal and external sensory organs. These sensory organs are tissues that consist of the sensory (input) components (dendrites) of neurons – for example the mammalian retina consists of a tissue of retinal neurons, the dendrites of which flatten out in the back of the eye to receive light (Gazzaniga, 2004). This stimulus is detected in the sense organ, transduced into electrical signals, then transmitted along neuronal extensions (axons), encoded, and eventually stored in and between the approximately 80 billion neurons in the brain (Gazzaniga, 2004; Kandel, Schwartz & Jessell, 2000). Learning is instantiated when the information stored in these neural networks is changed in a more-or-less permanent way (Borger & Seaborne, 1966; Mayer, 2008) – either by altering the number or strength of those neuronal connections. These changes then underpin more-or-less permanent changes to behaviour, cognition, emotions and physiology.

Conceptualising human learning as an evolutionary adaptation is the cornerstone of the emerging field of Evolutionary Educational Psychology – pioneered largely by Geary (1998, 2005, 2007 & 2009). He proposed that learning evolved because it enhanced the individual's ability to exert control over the physical world (by learning 'folk physics'), the animal world (by learning 'folk biology') and the human world (by learning 'folk biology). From this view, higher probability of survival and reproduction are the ultimate corollaries of human learning, and the 'purpose' for which it evolved.

Geary's work reflects meticulous, empirically- and theoretically-sound scientific research. Notwithstanding, it is fair to say that the EEP field has not enjoyed a significant uptake in educational practice, a result arguably related to the issues of valid translation – issues that will be addressed directly in this thesis. In making the connection between educational practice and evolutionary biology, EEP as a discipline provided the learning and educational sciences with an opportunity to be based on a broadly accepted, ultimate theoretical foundation (Darwinian evolution by natural selection). Importantly, it has also placed the learning and educational sciences firmly within the realm of evolutionary biology, and hence a subset of biology - the neurosciences.

The Emergence of Educational Neuroscience

Neuroscience by definition is a subset of biology – the word *neuro* means 'nerve' and nerves are defined as specialised cells (neurons) that have a highly specific function. The discipline of neuroscience – including so-called 'educational neuroscience' and 'neuro-education' - has been taken up by academics and commercial interests around the world, with a plethora of books, articles, dedicated journals and most recently postgraduate tertiary courses claiming to draw inferences about how the findings of this new and authoritative science can be applied to a panoply of practices. From economics (Loewenstein & Cohen, 2008), to philosophy (Churchland, 1989, 1996), to marketing (Ariely & Berns, 2010) to "neuroleadership" (Rock & Page, 2009), emotions (Damasio, 2006) and even recovery from trauma (Perry & Szalavitz, 2017; Van der Kolk, 1998), neuroscience has been embraced for its purported potential to resolve long-held mysteries in science and technology.

The 1990s was even termed the 'Decade of the Brain' (Jones & Mendell, 1999) as neuroscience emerged as a compelling and highly promising scientific discipline. Not surprisingly, this enthusiasm for the field has impacted the world of education, leading some to conject that a neurological understanding may even "revolutionise education" (Immordino-Yang & Damasio 2007, p. 1). In recent years, there has been no pause in the attempts to apply neuroscience to the classroom, both by academic and non-academic proponents. For example, there are many commercial "brain training" programs and books on the brain and how it applies into education (Jensen, 1998; Merzenich, 2013; Sousa, 2010; Willis, 2008). These sources typically claim that neuroscience can inform teachers on how best to teach, and in some cases explicitly claim that knowing about the brain is a pre-requisite for effective teaching (Dekker, Lee & Howard-Jones, 2012; Sousa, 2010; Willis, 2010).

The most influential scholar to urge caution about this enthusiastic adoption of neuroscience was John T. Bruer. In his seminal article (Bruer, 1997), he cautioned against the growing enthusiasm for the direct application of neuroscience into the classroom, and alerted proponents to the need for an intermediary step – that of cognitive psychology. His article quickly became highly influential, and the ideas he raised have since been taken up by other scholars (Bowers, 2016 for an overview), all of whom have explicated a foundational limitation: what is true at a cellular (neurological) level, may not directly translate to the classroom (the sociocultural level) – that such direction translation from neuroscience to education may in fact be a 'bridge too far'.

Even though, according to Google Scholar, Bruer has been cited over 1004 times since 1997 and is the most-cited article in the educational neuroscience literature; the interest in and enthusiasm for the application of neuroscience to education remains unabated. This is despite Bower's (2016) similar caution, claiming that education needs neuroscience far less than neuroscience needs education, and that many of neuroscience's claims have in fact been developed by education research, and at best have been *post hoc* confirmed by neuroscience.

The esteem in which neuroscience is held in education research and practice was well evidenced by the reaction to Bower's article: nine prominent researchers in the field (see Gabrieli, J, 2016; Howard-Jones et al., 2016) immediately attempted to debunk his claims and re-establish faith in the notion that neuroscience has, or will one day have, a seminal contribution to educational practice, research and policy.

The question about the validity of direct translation from neuroscience to education is far from moot. There is a long history of educational interventions that are purportedly justified by evidence from neuroscience and related areas – but that have little or no foundation in evidence. Program such as Visual-Auditory-Kinaesthetic Learning Styles, Left-Right Brain learning (see Geake, 2005 for an overview), various brain-training programs (Melby-Lervag & Hulme, 2013) and Brain Gym (Goldacre, 2010) are cases in point that remain popular amongst educators even to this day.

Despite the enthusiasm for the field, there is currently no viable evidence to support these claims of educational efficacy. This lack of evidence has not stopped millions of dollars and thousands of hours of school time being spent on this and similar programs. While there may be no evidence of direct harm of such ill-informed programs, the opportunity cost of such misapplication is inestimable, and raises important questions such as: what competencies do educators – and educational policy makers – need to acquire in order to see through invalid commercial claims in the future? Do policy-makers and teachers need to know about neuroscience to be effective translators from neuroscience or even effective teachers?

The Current Thesis

The importance of valid translation.

While researchers, practitioners and commercial interests have made claims about the direct impact of neuroscience into the classroom, others like Bruer (1997) and Bowers (2016) claim this has not occurred. The pervasiveness of purportedly neuroscience-informed interventions and programs, especially in the absence of empirical evidence for their educational efficacy, indicates a need to address the unresolved issues surrounding valid translation between the disciplines.

In contrast to the paucity of valid translation of neuroscience into education, the impact of the translation of psychology into education has been broad and long-standing.

Yet questions relating to that translation remain. Are these forms of translation valid? How does the translation of neuroscience compare to that of educational psychology? What limitations and constraints exist on each of them? How can knowledge from non-educational disciplines such as psychology and neuroscience be translated so as to enhance the education profession, its policies and practice? The issue of translation between education-related disciplines remains problematic and there is good reason to seek its resolution: and this is the aim of the current thesis.

To address these questions, the thesis will systematically review the educational neuroscience literature examining its impact on educational practice, and compare these results to the impact of educational psychology as examined by a meta-analysis and meta-synthesis of learning research. Finally, these results will be analysed and then used to propose a conceptual model of human learning that incorporates and aligns the various subordinate disciplines that comprise the Science of Learning. Such a conceptual model will, it is argued, allow the various disciplines a valid and meaningful place within the emerging field of the Science of Learning, from where scientific findings can be validly translated into education. In order to do this, it is first necessary to describe a conceptual framework by which the disciplines can be validly categorised according to their levels of complexity (Anderson, 2002), and a translation schema that describes a range of types of translation, and when each of them is, and is not, logical and valid.

A framework for examining translation validity.

The first questions addressed in this thesis surround the nature of translation – what is it, what types are there, and when is it valid, when is it not. At its essence, valid translation is the transformation of information and knowledge from one discipline into language understandable and meaningful in another discipline. To evaluate the validity of such translation, it is necessary to identify the various disciplines between which translation will occur. To this end, in Chapter 2 a Layered Abstracted Framework is proposed, in which the education-related scientific disciplines are separated in a logical (albeit ultimately artificial) way. This separation is based on levels of complexity – Layer I of which is the Physical (non-living) layer comprised of physical matter and energy, and includes research and practice conducted largely by physicists and engineers.

When atoms and molecules are combined in a specific way and under specific circumstances, they form living entities – cells. These constitute the Layer II of the model – the Cellular layer – the domain of cellular biologists, and in the case of education-related disciplines, cellular neuroscientists, recognising that the elementary unit of learning is a highly specialised cell known as the neuron. When cells combine with each other in specific ways, they become tissues, and when tissues combine, specialised organs are formed (e.g. the brain). Organs constitute Layer III of the framework, namely the Organellular or Cerebral layer. Similarly, when organs are combined, an individual organism is formed, and this is what constitutes Layer IV – the Individual layer - comprising individual persons with psychological, cognitive, emotional and physical properties. Finally, Layer V of the framework is constituted by populations of individuals and is named the Sociocultural layer, the domain of educators, sociologists, anthropologists and other professionals investigating organised groups of individuals. It is proposed that each of these layers contain characteristic, if not unique language, epistemologies, methodologies and assumptions that do not exist (that is, are pre-emergent) at the lower layers.

A schema of translation types.

Having proposed a conceptual framework by which all education-related disciplines, between which translation needs to occur, can be logically categorised, it is subsequently necessary to identify the possible types of translation, and describe the circumstances in which they are, or are not, valid. To this end, Chapter 3 builds on the Layered Abstracted framework, and proposes a new schema of translation types. This original schema outlines four types of translation: conceptual, functional, prescriptive, diagnostic. It is argued in this chapter that conceptual, functional and diagnostic translation between layers of the Abstracted Framework is logical, valid and of value. In contrast, and more importantly, it is further argued that *prescriptive* translation between non-contiguous layers is not valid, and is likely to generate logically flawed arguments leading to false conclusions, including but not limited to what have become known as neuromyths.

The impact of educational neuroscience.

The proposed abstracted framework and translation schema are then used in the analysis of the neuroeducational literature, and Chapter 4 reports the results. This study is a systematic review of the educational neuroscience literature based on 548 articles in the neuroscience-education literature (included according to specific criteria). These articles were selected and then reviewed in terms of the layer in which the research was conducted, the layer in which the conclusions were drawn, and the type(s) of translation used in order to draw those conclusions. The hypothesis being tested in this study was that there would be no published examples of valid prescriptive translation between non-contiguous layers in the framework. As outlined in Chapter 4, this hypothesis was not rejected, but the data also informed some helpful modifications to the translation schema.

The impact of educational psychology.

In order to compare the quality and extent of valid translation of neuroscience with that of educational psychology, Chapter 5 reports results from a second analysis, this time a meta-analysis of a representative sample of the educational psychological literature. 399

studies on learning strategies (Dunlosky et al., 2013) were meta-analysed, and these results compared to the authors' qualitative evaluation. These results, reported in Chapter 5, confirm the well-held notion that the translation of psychology into education has been prolonged, extensive and pervasive, albeit constrained by a focus on a narrow conceptualisation of learning.

These limitations and constraints of psychological and neursoscientific literature informed the final analysis that is reported in Chapter 6. In this study, a more expansive meta-synthesis of some 399 learning strategies was conducted. In contrast to the meta-analysis, this study was designed to analyse the learning strategies data into a proposed conceptual model of learning. In doing so, the surface-level, non-transfer and academic achievement limitations of the educational psychological literature may be addressed .

The methodology and results of this study were published in Hattie and Donoghue (2016) and are reported in Chapter 6. The results demonstrated that while the evidence on which learning strategies research is based remains constrained, there were sufficient data to underpin the conjecture of a conceptual model that allows for more ecologically valid translation into educational practice. In particular, this proposed model allows for translation of psychological research that investigates the psychological, emotional and motivational corollaries of human learning (the so-called thrill, will and skill), rather than just academic, knowledge-based outcomes. Further, the meta-synthesis confirmed the longevity, depth and robustness of educational psychological literature and its impact on educational practice, and that this body of knowledge was built without knowledge of, or reference to, any form of neuroscience. Despite its inherent limitations, this study and the proposal of a conceptual model, demonstrated one way in which those limitations might be overcome.

Towards a conceptual model for the science of learning.

In the final Chapter 7, conclusions are drawn, corollaries are explored, and future directions of research are proposed. In short, this thesis highlights the issues inherent in the valid translation of educational psychology and neuroscience into educational practice. While educational psychology has amassed an extensive corpus of robust and well replicated evidence from thousands of studies over decades of research, its application is constrained to a narrow conceptualisation of learning and teaching. Neuroscience in contrast promises to provide a more comprehensive, foundational and ultimate explanation of human learning, however the results suggest that to date, neuroscience has offered very little, if anything, that effective educators did not already know. There is very little evidence from neuroscience that prescribes what educators should do in the classroom (prescriptive translation) despite good evidence that neuroscience can in fact inform and explain known learning phenomena (an example of conceptual translation).

It is also concluded that the analyses demonstrate that not only can translation occur from bottom-up (neuroscience into education), but also from the top-down (education into psychology in to neuroscience). In many neuroscience studies, for example, education research provides knowledge of what works in learning, and this is then used by neuroscientists to find neural correlates for those known learning phenomena. In this way, education is informing neuroscience, and in so doing provides a form of Breuer’s bridge, but not in the way he anticipated. The real value of neuroscience for education may come from neuroscience translating *back up* the framework and informing educators on something they didn’t know – however the results from this thesis suggest that this is yet to happen. Indeed as Bowers (2016) stated, neuroscience needs education more than education needs neuroscience.

Translating down enables educators to recognise and embrace their own expertise, and using neuroscience has two benefits. First, it is 'seductively alluring' (Weinberg, 2008), so attracts attention from policy makers, educators, learners and funding organisations alike. Second, it serves as the gateway into evidence-based practice, something that has arguably not been well-established in education. By understanding neuroscience and cognitive psychology, educators are necessarily exposed to the rigours of the scientific method, logic, rational argument and the nature of evidence. If this newfound scientific literacy is transferred to teaching practice, then learning outcomes are likely to improve.

It will be concluded that the *Science of Learning* (the super-set) is far more important, and will have a far greater impact, than the *neuroscience of learning* (the sub-set). Educators, therefore, will be better served by adopting a 'Science of Learning' approach to education, of which neuroscience is a part, rather than attempting to apply neuroscience directly in the classroom. To facilitate this shift, it is proposed that future research focus on the development of a conceptual model that subsumes all learning-related scientific disciplines.

One such model, the Pedagogical Primes Model for the Science of Learning is proposed, reflecting the conclusion that the Science of Learning, as a holistic consortium of disciplines, is far more likely to impact educational practice than any one of those disciplines alone. This proposed model emerges out of the Hattie-Donoghue model outlined in Chapter 4, and is based on the Abstracted Framework outlined in Chapter 2. It is proposed that such a model allows for the valid alignment of educational practice with an ultimate theory (evolutionary biology) – thereby overcoming some of the limitations in the application of EEP.

The proposed model reconciles and aligns sociocultural, individual, neural, cellular and physical phenomena relevant to learning, distinguishes between learning's biological origins, predispositions & antecedents, vectors, desirable outcomes, and conceptualisations of learning, and introduces a new concept of *primes,* derived from linguistics (Goddard & Wierzbicka, 2007). It is further proposed that the conceptualisations of learning through this model will lead to the formulation of future research questions about the primary purpose of education – an issue that has beleaguered educators for centuries (Postman, 1999; Postman & Weingartner, 1969; Robinson, 2009; Glaxton, 2013). It will be argued that this model informs – but does not prescribe – debates around the philosophy of education, particularly around its purpose (Geary, 2007).

Recommendations for addressing this lack of explicated purpose – an omission that beleaguers both neuroeducation and educational neuroscience, are briefly addressed and future research recommended.

Limitations

Given the time constraints for the publication of this thesis, the date range of evaluated studies was necessarily limited to those published prior to 2017. While there have been some developments in the literature since that time, no studies have been published to the Candidate's knowledge that contradict the findings of this thesis. This time limitation is addressed in the sections "Post-Publication Addendum" that appear at the end of Chapters 5 and 6.

Chapter 2.

An Abstracted Conceptual Framework for the Learning Sciences

This chapter introduces a conceptual framework that allows for the logical, albeit artificial, categorisation of learning-related scientific disciplines. In subsequent chapters, this framework, along with the schema outlined in Chapter 3, will be used to systematically analyse the translation quality and types deployed in the neuroeducational literature. Titled the Abstracted Conceptual Framework for the Learning Sciences, it was originally published in a peer reviewed journal (Donoghue & Horvath, 2016), and this chapter is an essentially unedited reproduction of that published paper. The framework was first presented at the Science of Learning Big Day Out Conference in Sydney 2015. The candidate is the primary and lead author of this article, initially developed the concept, contributed 80% of the content, and was primarily responsible for the planning, execution and preparation of the work for publication.

Introduction

Educators have long sought to advance their professional knowledge, skills and effectiveness through an understanding of the findings of scientific endeavours. However, there have been instances of seemingly contradictory or incompatible research findings and theories in the learning sciences, particularly in the emerging field of educational neuroscience. For example, brain-based learning programmes (Jensen, 2005; Sousa, 2006; Willis, 2008, 2012) have become increasingly popular amongst educators, whilst researchers (Bowers, 2016; Bruer, 1997) make compelling arguments that neuroscience is unlikely to directly improve educational practice. Similarly, neuromyths beliefs about the brain that are unsubstantiated or disputed by evidence - still abound within the education profession (Pasquinelli, 2012). Other research suggests (often implicitly) that teachers' knowledge of the brain is an important, even critical, element of teaching quality, despite the absence of compelling evidence (Dommett, Devonshire, Sewter, & Greenfield, 2013; Howard-Jones, Franey, Mashmoushi, & Yen-Chun, 2009; Pei, Howard-Jones, Zhang, Liu, & Jin, 2015).

A recent example of this disparity is the debate that has flared over the learning effects of brain training. A research group based at Stanford University released a "consensus" stating that 75 scientists agree that brain training is not effective (Stanford Center on Longevity, 2015), and this was quickly followed by a second consensus statement of 117 scientists who claimed that it is (Cognitive Training Data, 2015). We will explore this debate in more detail later in this chapter.

Such a disparity of opinions between experts in their respective fields results in a distracting, unhelpful debate. We argue that this, and similar disparities, arise from a confusion of levels of analysis, where findings discovered at one level of analysis are generalised problematically to another level. We contend that many apparent issues can be resolved by the application of a common conceptual framework that recognises these levels of analysis. Such a framework would need to explicate and describe the disparate levels of analysis at which various scientific disciplines operate and advance their findings.

We propose one such framework, based on a standard model used extensively in the computer sciences for many years: a multi-layered, abstraction model for computer networks known as the Open Systems International (OSI) model (International Organization for Standardization, 1994). We will propose that the application of this model to the learning sciences may provide a framework for effective interdisciplinary communication and understanding.

A Layered Abstraction Framework for the Learning Sciences

The learning sciences comprise research methods, data and theories from a broad and varied number of disciplines - ranging from pure neuroscience that investigates the actions of a single neuron, to educational design investigating thousands of students, even to sociology studying entire societies and cultures.

In order to simplify this broad web of disciplines, we propose a layered abstracted framework that divides learning into five separate (but not naturally discrete) layers according to their levels of complexity. We assume that learning is, at its essence, a biological phenomenon, and so have established these levels of complexity according to the biological sciences. From this perspective, human learning is fundamentally a phenomenon of interactions in and between neurons, which are specialised living cells. Cells are entirely comprised of biochemicals that are, in turn, comprised of atoms. Further, neurons are located predominantly (but not exclusively) in the brain which is a biological *organ* - the result of the conglomeration of many cells. When one or more organs are integrated, an *organism* is the result, and when one or more organisms conglomerate with each other, a *population* (or society or culture) is the result.

These five categories can be summarised in the following sequence:

- Energy is transformed into matter - atoms and molecules (the domain of Physics);
- Molecules are organised to form biological cells (molecular biology);
- Cells specialise and colonise to form organs (cellular biology, internal medicine);
- Organs conglomerate and organise into organisms (physiology, psychology, biological psychology);
- Organisms congregate to form populations (sociology, ecology, education).

Or more simply:

energy → matter → cells → organs → organisms → populations

The Framework

We propose that each of these layers can be used to populate an abstracted, multi-layered framework, as described in Figure 2-1 below. Layer I, the physical base, is included in the framework in recognition of the capability of even non-living materials to store and alter information - both of which are necessary components of learning. There are various chemicals - especially complex proteins - that store information gleaned from the environment (Ryan & Grant, 2009). Further, even in physical machines involving single atoms, information storage is possible, and this forms the basis of silicon-based memory commonly found in computing machines, and even gives rise to “machine learning” where information is encoded, stored, processed and transmitted purely by those non-biological means (see Michalski, Carbonell, & Mitchell, 1984 for an overview of non-biological machine learning, and Churchland, 1996 for parallels between non-biological learning models and connectionist perspectives of the brain). When the information is stored in these physical media, and is changed in some way, learning is said to have occurred. Such non-biological learning has been shown to underpin biological learning - for example, computer algorithms have successfully simulated mammalian information processing and learning using digitally reconstructed neurons (see Markram et al., 2015 for an example). As work in this layer is generally the domain of physicists and mathematicians, there is probably little (if any) current relevance to education other than at a philosophical level (although this may change in the future), so will not be discussed further in this thesis.

Layer II, the cellular layer, conceptualises learning as any change to the information stored in and between unique biological cells. In unicellular life, such as simple bacteria, biomolecules exist in the cytoplasm (protosynsapses and proto-neurotransmitters) which are the precursors of the multicellular synapses (Emes & Grant, 2012). In multicellular organisms, single cells -primarily neurons - serve the essential function of encoding, storing, processing and transmitting information (Gazzaniga, 2004; Kandel, 2002). Biochemists, cell biologists and pure neuroscientists operate in this layer.

Layer III, the cerebral layer, conceptualises learning as consisting of more-or-less permanent changes to global patterns stored in and between organs within the body. The brain, for example, is composed of billions of specialised cells (neurons), the changing communication patterns of which instantiate learning (Gazzaniga, 2004; Hebb, 1949). Hence, research examining whole brains - such as with fMRI and EEG technology – resides in this layer, as would the study of *in vitro* neural networks. Systems neuroscientists, neurologists and computational neuroscientists reside in this layer.

Layer IV, the individual layer, conceptualises learning as a distinctly personal phenomenon, whereby all biological, psychological and emotional systems of an organism interact to generate measurable and predictable behaviours seen, where possible, in isolation from social and cultural influences. While the brain is the centre of learning, the interaction between the brain and other unique organs/organ systems (e.g. the cardiovascular system, the immune system, sensory systems and musculature) is an equally important factor in the generation and specification of learning and its behavioural outcomes. Cognitive and behavioural psychologists, neuropsychologists and educational psychologists operate in this layer.

Finally, Layer V, the sociocultural layer, is where most traditional educational interventions and experiences take place. In this layer, learning is conceptualised in its sociocultural context, recognising that individual human behaviours are fundamentally influenced by social, cultural and temporal phenomena (Bandura, 1986). The importance of these factors were recognised by Bronfenbrenner (1977, 1992), and were described in his Ecological Systems Theory. This person-centred sociocultural model recognises that genetic and other biological mechanisms impact and partially define the individual, as do the four subsystems (micro, meso, exo and macro) of that person's social and cultural milieu. All school- and classroom-based educational practice and research resides in this layer (in contrast, for example, with individualised laboratory-based learning, which resides in the preceding layer). Educators, educational researchers, sociologists, policy-makers, and school leaders reside in this layer, as they study the impacts of the broader social environment on the individual.

It is important to note that while it will be argued that distinguishing between these levels of analysis will enhance our understanding of the highly complex phenomenon of human learning, the distinctions between each of the layers are, ultimately, arbitrary and artificial. In nature these distinctions are far from clear or discreet, and considerable overlaps exist at every interface. For example, this is particularly relevant in our categorisation of psychologists to the Individual Layer - we recognise that this distinction is imprecise, and that a great deal of psychology is conducted in the Sociocultural Layer V, or at the Layer IV/V interface.

Features of the Framework

We will now outline the six major features of this framework.

Figure 2-1 *Compositional levels-of-organization for the learning sciences.*

Layer	Developmental phase	Layer name	Relevant discipline	Function
V	Populations	Sociocultural	Education, social sciences	Individuals interact with other organisms, in ecological, sociocultural contexts in which information is processed and transmitted
				This communication leads to group wide behavioural patterns, cultural norms and larger societal value sets (e.g. what should be included in curriculum?)
V	Organisms	Individual	Cognitive & behavioural psychology	The complete complement of biological, psychological and emotional systems embodied in an individual person. Communication between individuals generates larger sets of behaviour which are typically measurable and conscious
III	Organs	Cerebral	Systems, cognitive and behavioural neurosciences	Groups of neurons form connections with other neurons and non-neuronal cells to form larger networks. Patterns of network activity and excitability allow for the transmission and processing of information within and between specific organs in the body. This communication leads to specialised, occasionally unmeasurable and largely subconscious proto-behavioural patterns
I	Cells	Cellular	Biology/pure neuroscience	Unspecialised cells can individually store, encode, process and transmit information by use of proto-neurotransmitters which float freely in the cytoplasm. Specialised neurons capable of storing, processing and transmitting information
I	Matter	Physical	Physics	Information obtained from the external environment can be encoded, stored in, and occasionally transmitted between atoms, particles and complex molecules. Examples include machine learning (supervised and unsupervised) in computing devices

Feature 1. Downward compatibility.

First, in accordance with the abstracted structure of the framework, phenomena established within each layer can never contradict phenomena established in a lower layer. For instance, elucidating how information is stored within a neuronal network (Layer III) cannot contradict the basic concepts elucidating how individual's neurons work (Layer II). As a more educationally relevant example, for social learning theory (ecological, Layer V) to be true, it must be consistent with what is known about neural learning (Layer II) and could not rely upon a learning mechanism that has been disproved by neurology (e.g. a student's ability to mind-read). We refer to this principle as downward compatibility.

Feature 2. Upward unpredictability.

Phenomena established within each layer may not necessarily be predicted by, or understandable from, phenomena established from a lower layer. For example, simply knowing how a single neuron responds to a light stimulus (Layer II) is insufficient to predict how a million neurons embedded in a network will respond to an identical stimulus (Layer III). Returning to our earlier example, simply by knowing how a neuron produces an action potential (Layer II) is insufficient to predict any of the components of social learning theory (Layer V). This establishes the principle that one layer's emergent properties cannot be predicted from any lower layer - we refer to this as the principle of upward unpredictability.

Feature 3. Reconciling terminological divergences.

Dividing layers in this manner allows for learning scientists in whatever discipline to create definitions that are simultaneously meaningful in their own discipline and intelligible to disciplines from all other layers. For example, Kolb (1984, p. 41) defines learning as “a process whereby knowledge is created through the transformation of experience”, whereas Hebb (1949, p. 43) defines learning as “When an axon of cell A is near enough to excite a cell B and repeatedly or persistently takes part in firing it, some growth process or metabolic change takes place in one or both cells such that A’s efficiency, as one of the cells firing B, is increased”.

Without a coherent framework, these two definitions are difficult to reconcile, and are relevant and meaningful only to the discipline in which they were formed. However, by applying our abstraction framework, it becomes clear Kolb is defining learning at the individual layer whilst Hebb is defining it at the cellular layer. Given that they reside in different layers, neither definition is incorrect nor are they contradictory. Assuming Hebbian theory to be valid, Kolb’s definition simply cannot contradict Hebb whilst Hebb’s need not predict Kolb’s. This type of clear, coherent organisation may help prevent confusion and pointless debate over apparently conflicting data and theories obtained from divergent language used in the different layers.

Feature 4. Translational contiguity.

For any type of learning research to be relevant to and meaningful in education (Layer V) and thereby qualify as “educational neuroscience”, it must traverse and be translated through each intervening layer via each interface. According to Anderson’s Orders of Magnitude analysis (Anderson, 2002) it is problematic to use information obtained from lower orders of magnitude (e.g. atomic machine learning which occurs on the scale of milliseconds) to draw conclusions or make inferences about information obtained from higher orders of magnitude (e.g. ecological learning where effects can take centuries). We refer to this as the translational contiguity principle, whereby evidence from one layer must be validly translated to each adjacent or contiguous layer, via their interface. Aside from ignoring the influence of emergent properties at each layer, we propose that leaping across layers without reconciling the intervening interfaces is likely to lead to the drawing of false conclusions and the promulgation of neuromyths. We speculate therefore that the valid application of this framework would prevent such neuromyths emerging.

Consider the example of hydration. It is known that dehydration can have a significant impact on cell function (Layer II), leading some commercial education programmes to conclude that learners should “therefore” have drink bottles on their desks and drink lots of water when in class (Layer V) (Pasquinelli, 2012). However, when one applies our framework to explicate which layer is applicable to both of these statements, and which interfaces must be traversed to link the two, an illogical, non-contiguous leap becomes evident. Knowing that dehydration affects cells, one must next define how that impacts the whole brain (negotiating the Layer II/III interface), then the whole individual (and the Layer III/IV interface) and finally how that impact is expressed in the sociocultural classroom (Layer IV/V interface).

However, in arriving at the “educational implication”, the proponents of “drink bottles in classrooms” did not consider these transitional interfaces. Had they done so, basic medical evidence would have shown that while hydration is critically important in the functioning of the neuron (Layer II), there exist other organs (Layer III) (e.g. the pituitary gland) and systems (Layer IV) (e.g. the individual’s sensation of thirst) that ensure cells remain hydrated and therefore functional. It is not physiologically necessary to drink large amounts of water (Valtin, 2002), nor does doing so enhance a student’s learning (Goldacre, 2010; Howard-Jones, 2010; Howard-Jones et al., 2009; Rato, Abreu, & Castro-Caldas, 2013). High levels of dehydration (1–2% of body mass) will certainly have physiological effects, including cognitive effects (see Ganio et al., 2011; Lieberman, 2007 for an overview), but to assert that such a conclusion is drawn from, let alone based on, neuroscience is a non sequitur logical fallacy.

By applying the framework to this debate, it is apparent that while cellular knowledge (Layer II) might validly generate the hypothesis that drinking water may enhance classroom learning, it cannot validly prescribe that teachers provide drink bottles, or that students drink large amounts of water in class (Layer V). Such conclusions ignore the emerging properties at the intervening layers - for example, the impact of other bodily systems that create the experience of thirst (Layer IV) and obviate dehydration, or the fact that the body receives liquids from many sources, not just drinking water (Layer III), or that groups of children may, for example, misuse the water bottles and thereby impact the learning of classmates (Layer V). In order to make prescriptive conclusions at Layer V, it would be necessary to conduct the research at that layer - evidence that is not cited by water-bottle proponents - and measure the actual improvement in learning directly. The evidence from the lower layers may be conceptually or hypothetically informative, but it cannot be prescriptive.

This case illustrates how leaps between non-adjacent layers, even when seemingly intuitive, can be a fraught exercise. Verifiable findings, ideas, and theories must progress vertically and sequentially through the framework. To achieve this stepwise traversal, researchers need to explicate in which layer their research belongs. Doing so will not only allow fellow researchers to quickly organise others’ work to determine how far theories and findings do (and do not) reach, but also will make data more meaningful and relevant to educators. This would entail researchers explicitly declaring not only the layer in which their research was conducted, but also the layer in which their conclusions are drawn and extrapolated.

We argue that research from lower layers extrapolated into higher, non-neighbouring layers has the potential to lead to false conclusions and neuromyths. Hence, allowing educators to know from which layer work was conducted may help them determine the relevance/utility of each new finding. All-too-often, agencies have proven ready to arrive at apparent suggestions for educational practice based upon unwarranted projections. Categorising research in this way will afford the added benefit of highlighting gaps and redundancies in the research.

Feature 5. Experts need not operate in multiple layers.

Just as in the OSI model, researchers and practitioners in each layer need not know the details of work in other layers. Rather they need only master the concepts at their own layer and, when interested in translation, concern themselves with the interfaces between their layer and its neighbours. According to this framework, no practical advantage would be afforded to educators (Layer V) having a strong knowledge of, say, action potentials (Layer II) or network dynamics (Layer III) (though their practices must be consistent with knowledge about action potentials and network dynamics). For example, knowledge of the biochemistry of the action potential (Layer II) is unlikely to inform an educator's ability to conduct a think-pair-share classroom exercise (Layer V). This point has recently been explored in depth by Bowers (2016) who argues that "neuroscientists cannot help educators in the classroom" (p. 601).

Our view here appears at odds with the often expressed view that educators ought to increase their awareness of neuroscience (Howard-Jones et al., 2009; Laurillard, 2016; Willis, 2012). Instead, educators most need to concern themselves with work and research occurring within the sociocultural Layer V, as we are unaware of any research showing that neuroscience literacy improves teaching effectiveness. Moreover, there is growing evidence that improving students' neuroscientific literacy is, by itself, unlikely to have a marked impact on learning outcomes.

Brainology, for example, is a programme co-founded by Carol Dweck (Dweck, 2007; Mindset Works Inc, 2016) that aims to enhance the neuroscientific literacy of students and thereby shift their mindsets from a fixed or entity theory of intelligence, to a growth or incremental theory (see Dweck, 2000 for a full description). Few peer-reviewed studies have been conducted on this programme, however when Donohoe, Topping, and Hannah (2012) examined its effects on 33 students aged 13 - 14, they found no significant long-term changes in mindset, despite a small but significant shift immediately after the programme. There were no significant changes in resilience or mastery, either short- or long-term.

Similarly, Dommett et al. (2013) examined the impact of a series of neuroscience workshops that "best support the development of a flexible mindset including a belief in incremental intelligence" (p. 124) with 383 year 7 students (aged 11–12). While they found a "mild but significant" (p. 137) shift towards a growth mindset, they found that neuroscience-based interventions produced no shift in students' motivational measures or their mathematics performance. There is some evidence that mindset interventions can at times help students maintain positive motivation (Schmidt, Shumow, & Kackar-Cam, 2016), but the notion that such interventions result in achievement gain is not supported.

Feature 6. Understanding limits of valid findings.

Finally, because each layer has its own emergent properties, it is conceivable that a learning phenomenon observed at one layer may not be expressed at a higher layer. For instance, although a single neuron may demonstrate an excitatory response to a certain chemical (Layer II), when embedded within millions of similar (Layer III) and/or dissimilar (Layer IV) cells, each demonstrating their own unique reaction to that chemical, this single neuron may switch to being inhibitory (Ganguly, Schinder, Wong, & Poo, 2001). Most importantly, such a switch is unlikely to have any detectable influence in the classroom (Layer V). There may be many reasons for this lack of interdisciplinary transfer, but this does not detract from the validity of the findings in each layer. Rather, this creates the possibility for better research questions: for instance, when faced with two findings that are apparently inconsistent, researchers can ask the more productive question "what is happening at the interface such that this effect is not being expressed at the higher layer?", rather than the hollow question of "which perspective is right, and which is wrong?" (see Post-Publication Addendum below for more specific discussion on research questions).

Resolving Contradictions with the Framework

Earlier in this chapter, we briefly outlined the current "debate" in the learning sciences concerning brain training. More specifically, two competing consensus statements have recently been published, one arguing that brain training programmes are ineffective (Stanford Center on Longevity, 2015) and the other arguing these programmes are effective (Cognitive Training Data, 2015). Although it is certainly possible that this contradiction is arising from each group of researchers interpreting the same data differently, it is more likely this contradiction is arising from each group of researchers interpreting data from different layers of the abstracted framework.

In order to determine if this was the case, we organised the list of signatories for each consensus statement according to their primary field of research. We found that of the 75 scientific signatories proclaiming brain training is ineffective, 54 (72%) primarily conduct behavioural research (including behavioural psychologists, educational researchers and others) whilst 21 (28%) primarily conduct neurophysiological research (including neuroscientists, psychiatrists and others.). Conversely, of the 117 scientific signatories proclaiming brain training is effective, 88 (67%) primarily conduct neurophysiological research whilst 29 (22%) primarily conduct behavioural research (note: the latter consensus contained an additional 14 signatories from non-scientific fields: these were excluded from this analysis).

This suggests that the majority of scientists proclaiming brain training does not work (72%) conduct research in, and are arguing from, Layers IV and V, whilst the strong majority of scientists proclaiming brain training does work (75%) conduct research in, and are arguing from, Layers II and III. Accordingly, far from being a debate, it is likely both consensus statements possess genuine validity - each is simply arguing from a different, non-commensurate layer, thereby suggesting brain training likely impacts the neurophysiological characteristics of the brain but may not impact larger behavioural or social patterns. If the researchers explicated the layer in which their research was conducted, and constrained the conclusions and implications of that research to that layer, then it is likely the discrepancy would never have arisen in the manner in which it surfaced publicly.

In this example, an apparent discrepancy appears in a different light when we understand and make explicit the layer from which evidence was likely derived. In the end, this is not a discrepancy between right and wrong - both arguments possess validity. From here we need only build the bridges between each interface to determine why findings at Layers II and III are not necessarily being expressed in Layer IV and possibly non-existent in Layer V.

Future Application

Whilst beyond the scope of this present chapter, a possible further application of this simple framework is to incorporate other dimensions of learning into the framework, locating them according to their applicable layer. For example, the following learning phenomena could be included along a horizontal dimension of the framework:

- Definitions and conceptualisations of learning ("what is learning?");
- Mechanisms of learning ("how does learning occur?");
- Learning influences ("what factors can moderate and mediate learning?");
- Learning interventions ("what interventions can directly enhance learning?");
- Learning outcomes ("what are the consequences of learning?").

Each of these questions is likely to generate different answers depending on the layer within the framework upon which the question is posed. For instance, the mechanisms of learning at Layer II (cellular) might include biochemical reactions in protosynapses (Emes & Grant, 2012) whilst the mechanisms of learning at Layer V (ecological) necessarily include complex social interactions with others, mediated by cultural norms. Similarly, while a learning outcome at the individual Layer IV might be a child's specific academic achievement score, a Layer V outcome of learning might be the economic or cultural benefits that arise from a well-educated population. Distinguishing these various learning phenomena according to the layers of the framework will likely provide further clarity of educational practice and theory, and generate interesting hypotheses about, for example, links between neuroscientific knowledge and learning/teaching effectiveness. The extension of the framework in this way can inform the construction of comprehensive conceptual models of learning, and this development has already begun (Hattie & Donoghue, 2016).

Concluding Remarks

This framework simplifies and makes manageable the complexity of the learning sciences, recognising that there is more to learning - and much more to education - than simply interactions between neurons. Learning, in its essence, is a complex neurological phenomenon, while education is an even more complex sociocultural one. The application of this framework - where these phenomena are explicitly separated and conceptualised - may assist the learning sciences in developing a common translational and conceptual framework, underpinned by shared language and thereby avoid ill-framed and unhelpful debates. By contextualising these phenomena into an integrated framework, educational neuroscience can now take its rightful place as one important - but not the only - component of the broader science of learning.

Acknowledgement.

The Science of Learning Research Centre is a Special Research Initiative of the Australian Research Council [grant number SR120300015].

Post-Publication Addendum

As this chapter outlines a proposed conceptual framework that can be used in subsequent empirical research, no empirically-testable questions were included in the published paper. To expand on the questions alluded to however, the following research questions underpinned the development of the framework:

- Are there valid and measurable levels of analysis, as described by Anderson (2002), within educational neuroscience research?
- To what extent does educational neuroscience research invalidly cross the boundaries between these layers?
- How can the division of research into discreet abstracted layers help resolve the issues of translation within educational neuroscience?

Chapter 3.

A Bridge Too Far–Revisited: Reframing Bruer’s Neuroeducation Argument for Modern Science Of Learning Practitioners

This chapter builds on the layered framework outlined in Chapter 2, and introduces a schema of translation that comprises four essential translation types: conceptual, prescriptive, functional and diagnostic. This schema will be used in subsequent chapters to systematically analyse the translation quality and types deployed in the neuroeducational literature. Titled ‘A bridge too far—revisited: reframing Bruer’s neuroeducation argument for modern science of learning practitioners’, it was originally published in a peer reviewed journal (Horvath & Donoghue, 2016). This chapter is an essentially unedited reproduction of that published paper. Since the publication of this chapter, there has been continued debate on the issue of translation within educational neuroscience, most notably that initiated by Bowers (2016). This subsequent research is discussed in further detail later in this thesis (see Post Publication Addenda to Chapters 5 and 6 for full discussion). To date, there has been nothing published that challenges the findings of this thesis.

The candidate is the primary author of this article, co-developed the concept, contributed 60% of the content, and was primarily responsible for the planning, execution and preparation of the work for publication.

Introduction

In Education and the Brain: A Bridge Too Far, John Bruer (1997) argued that, although current neuroscientific findings must filter through cognitive psychology in order to be applicable to the classroom, with increased knowledge the neuroscience/education bridge can someday be built. Here, we suggest that translation cannot be understood as a single process: rather, we demonstrate that at least four different 'bridges' can conceivably be built between these two fields. Following this, we demonstrate that, far from being a matter of information lack, a prescriptive neuroscience/education bridge (the one most relevant to Bruer's argument) is a practical and philosophical impossibility due to incommensurability between non-adjacent compositional levels-of-organization: a limitation inherent in all sciences.

After defining this concept in the context of biology, we apply this concept to the learning sciences and demonstrate why all brain research must be behaviourally translated before prescriptive educational applicability can be elucidated. We conclude by exploring examples of how explicating different forms of translation and adopting a levels-of-organization framework can be used to contextualize and beneficially guide research and practice across all learning sciences.

In 1997, John Bruer published *Education and the Brain: A Bridge Too Far* – a theoretical exposition of neuroeducation that has proven seminal to the learning sciences (Bruer, 1997). In this piece, Bruer cautions that the gap between neuroscientific research and educational practice is too wide to traverse. However, he argues that this gap can be spanned by utilizing cognitive psychology as an effective middle-ground: more specifically, neuroscience can be used to elucidate and guide cognitive psychology, which, in turn, can be used to elucidate and guide education. Interestingly, Bruer couches this argument in terms of a 'dearth-of-information' – suggesting the major impediment to the actualization of neuroeducation is lack of knowledge.

For instance, Bruer notes "Neuroscience has discovered a great deal about neurons and synapse, but not nearly enough to guide educational practice. *Currently*, the span between brain and learning cannot support much of a load" (p. 15; emphasis ours). Similarly, Bruer states "Educational applications of brain science may come eventually, but *as of now* neuroscience has little to offer teachers in terms of informing classroom practice” (p. 4; emphasis ours). Whether he meant to convey a sense of hope or was merely trying to temper the potentially controversial nature of his argument, Bruer’s language gives the impression that, with enough knowledge, the bridge between neuroscience and educational practice is achievable.

Doubtless inspired by this language, many researchers in the learning sciences have interpreted Bruer’s article as a challenge to effectively link the brain to instructional practice (Antonenko et al., 2014; Samuels, 2009; Szucs & Goswami, 2007; Willingham & Lloyd, 2007). Unfortunately, despite decades of work, an effective neuroscience/education bridge remains a frustrating chimera–and dogged pursuit of this goal has led to an increase in the proliferation of the very ‘neuromyths’ that Bruer was cautioning against (Alferink & Farmer-Dougan, 2010; Howard-Jones, 2014; Pasquinelli, 2012).

In fact, so frustrated have some neuroscientific researchers become, that a recent argument has been put forward suggesting that failure to construct the bridge is partly due to a lack of neuroscientific literacy amongst educators (a point examined in more detail later in this paper (Busso & Pollack, 2015; Dekker et al., 2012; Devonshire & Dommett, 2010) . In this article, we will re-visit Bruer’s argument: however, we will present it not as a puzzle to be solved, but as a limitation inherent in all fields of scientific inquiry. We will demonstrate why, practically and philosophically, attempting to prescriptively connect neuroscience and education (at least, education as it is most commonly practiced) is not only hollow, but also irrelevant. In addition, we will demonstrate that acceptance of this premise can aid in the larger goals of the learning sciences by offering a concrete and coherent framework through which to conceive of, undertake, and effectively provide prescriptive translation of research.

Prescriptive, Conceptual, Functional and Diagnostic Bridges

It is proposed that there are at least four different ‘bridges’ that can conceivably be built between neuroscience and education: prescriptive, conceptual, functional, and diagnostic. A prescriptive bridge attempts to specify practices to be undertaken at the educational level on the basis of evidence derived from the neurophysiological level. In other words, prescriptive translation aims to instruct an educator and learner on what to do and how to do it. A conceptual bridge allows for individuals to understand or conceive of phenomena at the educational level through theories generated at the neurophysiological level. In other words, conceptual translation allows educators and learners to broaden their explanations for and interpretations of why certain educationally relevant practices work –however, this type of translation is silent on what these practices should or should not entail. For instance, although some educators may be inspired to use the concept of Hebbian-plasticity to justify the success or failure of a specific lesson, this interpretation does not impact the content, form, or efficacy of the lesson itself.

A functional bridge allows for phenomena at the neurophysiological level to constrain behaviours and cognitions at the educational level. In other words, functional translation allows for alterations of brain form and/or function to expand or restrict the number and type of educationally relevant practices an educator or learner can successfully undertake – however, again, this type of translation is silent on what such practices should or should not entail. For instance, if a learner were to suffer damage to the visual cortex leading to blindness (neurophysiological), then any learning activities would be unavoidably constrained to activities which do not rely on vision (education). Of particular importance in this example, however, is that damage to the visual cortex does not instruct the learner as to which non-visual learning activities to undertake, how to best undertake them, or how to measure their impact.

As the distinction between prescriptive and functional bridges is somewhat subtle, it may be worthwhile to expand using a specific example. Some students with attention disorders opt to use pharmaceuticals to mitigate their symptoms and improve educational performance. This performance is improved by changing activity at the neural level. At first blush, the use of a pharmaceutical may appear to be a prescriptive bridge. However, a closer examination reveals that taking a pill constrains an individual's attentional networks thereby making them more receptive to learning – but this does not engender learning itself. Pharmaceuticals do not inform the educator or the student as to which activities to use, how to use them, or how to measure them in order to learn language, math, or geography. Accordingly, pharmaceutical intervention represents a functional, rather than a prescriptive, bridge.

Finally, a diagnostic bridge allows for cognitions and/or behaviours at the educational level to be backward-mapped to and correlated with phenomena that exist at the neurophysiologic level. In other words, diagnostic translation aims to describe how a student is learning (or failing to learn) based upon individual functional brain patterns – however, once again, although this type of translation may inspire novel ideas for learning interventions, it is silent on what these interventions should entail and how they should be enacted. For instance, if a learner was to demonstrate difficulty engaging with a reading lesson (education), knowledge of his/her neuronal activation patterns during reading activities (neurophysiological) could be utilized to potentially determine the underlying root/s of this difficulty. Of importance, however, is that this knowledge does not inform an educator or student on what to do to effectively improve or otherwise alter those neuronal patterns.

As might be expected, the primary form of translation most desired and expected by practising educators is prescriptive (Hook & Farah, 2013; Pickering & Howard-Jones, 2007). As such, the main argument of this article centres around the prescriptive bridge only. More specifically, we will be arguing that findings at the neuroscientific level are irrelevant - and cannot be prescriptively translated - to classroom behaviours.

It is important to note that the conceptual, functional, and diagnostic bridges are not only possible, but also already exist across all levels of the learning sciences. With regards to the conceptual bridge, educators and learners at all levels are utilizing the neuroscientific paradigm to understand and explain their current practices (Abiola & Dhindsa, 2012), even though that framework has not directly instructed them how to perform or measure the success of those practices. With regards to the functional bridge, many educators and learners at all levels are utilizing the neuroscientific paradigm to understand and explain their current practices (Abiola & Dhindsa, 2012), even though that framework has not directly instructed them how to perform or measure the success of those practices. With regards to the functional bridge, many educators and students consume pharmaceuticals or utilize electromagnetic devices which modulate function at the neurophysiological level (McCabeetal, 2005; Pascual-Leoneetal, 2012). These tools typically expand the number of behavioural and/or cognitive practices a person can perform, even though they do not directly instruct him/her as to which practices to perform, how to perform them, or how to measure the success of each. With regards to the diagnostic bridge, a number of individuals are utilizing knowledge of individual neurophysiology to determine the root causes of specific learning patterns, especially disabilities (Temple et al., 2001). This information may inspire learning interventions, though it does not dictate the parameters or content of those interventions.

Again, throughout this chapter we will not be arguing that knowledge of neuroscience cannot influence conceptualization, function, or diagnostic ability at the educational level – rather, we will be arguing that it cannot be prescriptive at the educational level.

Remembering Bruer's Argument: Time and Effort

Bruer opens his article by outlining two major neurobiological arguments prevalent in the 1990s used to support the case for a neuroscience-guided education. First, he explores how the concept of early-life (0–10 years) synaptogenesis influenced the argument for critical periods: highly constrained time windows during which educators can (must) expose students to specific experiences lest they fail to develop those skills required to demonstrate educational success (pp. 5–9). Next, he examines the concept of adolescent synaptic pruning and research demonstrating that 'enriched' environments can temper this pruning: an occurrence which suggests educators must enhance sensorial aspects of the learning environment lest students lose capacity to learn novel skills (pp. 9–10).

After outlining these arguments, Bruer demonstrates why each are over-extended, largely misrepresented, and do not prescriptively impact educational practice. With regards to critical periods, he reveals that the basic neuroscientific research exploring this concept has only ever been suggestive of critical periods within basic sensory and motor systems, such as vision or audition. As such, there is no evidence such periods exists (nor any theories as to why they would exist) within larger cognitive/behavioural systems required for success in educational settings, such as reading and arithmetic skills. With regards to 'enriched' environments, he points out that every environment containing a novel feature or activity can be considered 'enriched' and may temper synaptic pruning – regardless of the type/amount of novelty and the age of the learner (adults demonstrate a similar effect as younger students). Accordingly, though intriguing, this notion offers no concrete or applicable advice to educators beyond "don't deprive students of novel experiences".

Bruer continues by demonstrating that neuroscientific findings are more applicable to the field of cognitive (behavioural) psychology; and that, in turn, cognitive psychology findings are more applicable to education (pp. 11–15). For instance, Bruer argues that though neuroscientists can demonstrate the time-course and evolution of synaptic growth and plasticity, cognitive psychologists can demonstrate the time-course and evolution of numerical competency. Though the former is doubtless reflected in the latter, only the latter can engender specific behaviours relevant and applicable to educators within the modern classroom.

Interestingly, he concludes by leaving the reader with hope; suggesting that failure to build the direct bridge between basic neuroscience and education is due only to a lack of knowledge. As outlined above, Bruer's language implies it is only a matter of time, effort, and information before the bridge can and will be built.

Reframing Bruer's Argument: Incommensurable Levels-of-Organization

The continued absence of a prescriptive neuroeducation bridge is not, as theorized by Bruer, due to a dearth of information – rather, it is due to a feature common to and accepted in all scientific fields: incommensurable levels-of-organization (Fodor, 1974, 1997; Rohrlich, 2004; Rosenberg, 1994; Wimsatt, 1994). However, these terms are notoriously ambiguous in both the philosophical and scientific literature – as such, it is important we explicate how these terms will be used in this chapter. Common conceptions of levels-of-organization within living systems are compositional in nature (e.g., Kim, 1999; Oppenheim & Putnam, 1958; Wimsatt, 1994). More specifically, objects at each unique 'level' are thought to be composed of material from the preceding level. For instance, within biology, levels-of-organization typically progress accordingly:

Cell → Tissue → Organ → Organism → Population → Community → Ecosphere →Biosphere

As can be surmised, tissues are composed of cells; organs are composed of tissues; etc. Accordingly, a foundational explication of 'levels-of-organization' within living systems can be stated as a step-wise increase of compositional material.

An important corollary of this type of organization is emergence: a process whereby novel and coherent structures, patterns, and/or properties arise at ascending levels that are not exhibited within or predictable by preceding levels (for discussion: Bedeau & Humphreys, 2008). For instance, the unified size, shape, and functional coherence of an entire ant colony cannot be explained or predicted by exploring the behaviour of an individual ant (Johnson, 2002). Accordingly, 'levels-of-organization' within living systems can be more explicitly stated as a step-wise increase of compositional material leading to emergent properties unpredictable by preceding levels.

To account for emergent properties at ascending levels, a series of unique scientific fields and specialties have been developed to explore and explain phenomena within each level – for instance, cytologists are devoted to studying cells, histologists are devoted to studying tissues, etc. However, in order to successfully undertake work, researchers at each level are necessarily required to utilize a unique set of questions, definitions, tools, and success criteria (Pavé, 2006). For example, when attempting to define the infectious disease measles, researchers at the cellular level may use crystallography to map proteins on the viral envelop to determine the binding site of this virus to individual epithelial cell receptors (Tahara et al., 2008), whilst researchers exploring this virus at the organ level may use post-mortem gross pathology to characterize the morphologic spread of viral driven necrosis within the lung (Kaschula et al., 1983). Similarly, whereas researchers at the tissue level may use an eyepiece micrometer to elucidate viral infolding of varied lymphoid tissues (White & Boyd, 1973), researchers at the population level may use aggregate survey and medical record data to map the spread and prevalence of this virus across a country (Santoro et al., 1984). Accordingly, 'levels of-organization' within living systems can be further refined to mean a step-wise increase of compositional material leading to emergent properties unpredictable by preceding levels requiring unique language, tools, data, and success criteria to explicate.

Although, each of these above examples represents a valid way to conceive of, define, and elucidate measles, it is clear that each is unique and difficult to meaningfully correlate with the others. For this reason (amongst others), the concept of incommensurability was developed (Feyerabend, 1962; Kuhn, 1962). Incommensurability is perhaps best understood by laying out three basic concepts (as derived from both Feyerabend and Kuhn):

- Different paradigms are based upon different presumptions concerning what scientific questions are 'valid' and about what standards a solution needs to satisfy;
- The interpretation of observations is differentially influenced by the assumptions of different paradigms;
- The vocabulary and methods used within each paradigm are different: therefore, different paradigms cannot be compared in any meaningful manner.

Though this theory was largely developed to explain the evolution of conceptual frameworks within specific scientific domains, replacing the word 'paradigm' in the above concepts with the word 'levels' reveals why work within each level is largely independent from work in other levels. Researchers at each level are necessarily required to utilize a unique set of questions (presumptions), definitions (vocabulary), tools (methods), and success criteria (solutions). For this reason, work at each level can be understood as incommensurable with work at other levels. However, it is worth pointing out that incommensurability is not the same as incomparability. Often times, the varied languages and methodologies utilized at different levels will spring from the same coherent environmental references (e.g. germ-theory of disease) and explore the same topic (e.g. measles). Therefore, work between layers may be compared and will often prove non-contradictory (in fact, comparability gives rise to the conceptual bridge outlined earlier in this piece).

In summary, we refer to ‘ levels-of-organization’ in a living system as a step-wise increase of compositional material leading to emergent properties unpredictable by preceding levels requiring unique language, tools, data, and success criteria to explicate. Furthermore, adopting the traditional definition generated by Feyerabend and Kuhn (for review, see Oberheim & Hoyningen-Huene, 2009), we hold that unique levels-of-organization are incommensurable in that they utilize different presumptions, vocabularies, methods, and solutions.

Prescriptive Translation Between Incommensurable Levels-of-Organization

The utilization of incommensurable methodologies and analyses within each level imposes limitations on prescriptive translation between levels. More specifically, in order to prescriptively translate between adjacent levels, one must adopt a number of assumptions. Returning to measles – it is conceivable that knowing how the virus binds to a single epithelial cell may be of some use to someone attempting to track cellular-membrane fusion within epithelial tissue (made up of 1000s of individual epithelial cells). However, until one is able to simultaneously measure activity within each individual cell within a larger tissue, assumptions must be made in order for the former to influence the latter: such as, that the behaviour of individual cells will not drastically change amongst millions of competing cells, that the global extracellular environment of a tissue is not drastically different from that of an isolated cell, that the structural properties of a tissue will not greatly impact the prevalence or function of membrane receptors, and so on.

Certainly the translation between non-adjacent levels becomes increasingly precarious as the number and gravity of assumptions compound – however, more importantly, due to the emergence of unique and irreducible properties at ascending levels-of-organization unpredicted by preceding levels, translation between non-adjacent organizational levels is often devoid of any prescriptive utility (Atlan, 1993; Mazzocchi, 2008). For instance, researchers focused on elucidating the workings of an individual cell do not concern themselves with novel properties that emerge when 1000s of cells work in tandem to form a tissue (e.g., permeability, contractibility, mineralization, etc.). However, it is precisely these emergent properties that may influence researchers interested in the process by which many different tissues combine and interact to form an organ. Similarly, properties irrelevant to and unpredictable by the study of unique tissues that emerge only when exploring a complete organ (e.g., structure, function, chemical production, etc.) are precisely those properties that may prove influential to researchers interested in the process by which many different organs combine and interact to form an organism.

Returning once more to the example of measles, although the importance of viral binding within a single epithelial cell may be of use for someone interested in understanding how measles present within larger epithelial tissue, the prescriptive importance of this knowledge for someone interested in how measles present across the entire skin (made up of thousands of different types of cells) is less clear. Continuing to higher organizational levels, the prescriptive importance of viral binding within a single cell is even less clear to someone interested in the effect of measles across the entire nervous system (organ system), the entire human body (organism), or an entire country of human bodies (population). Of prescriptive importance to researchers at each organizational level are those unique properties which emerge only at the immediately preceding level (Huneman, 2008). For instance, the researcher interested in how measles presents across the skin may be influenced by the effects and emergent properties of measles on the dozens of tissues that constitute the skin.

Interestingly, it is in this pattern we discover how nonadjacent levels can prescriptively interact: via translation through intermediary levels. More specifically, research at the cellular level may influence research at the tissue level (with the acceptance of certain assumptions), whilst research at the tissue level may influence research at the organ level (again, with certain assumptions), etc. As such, although attempting to build a prescriptive bridge between the cellular and organ levels may be futile, prescriptive bridges can be built over the cellular/tissue and tissue/organ gaps.

Although, this may appear obvious, it is extremely important to make this idea clear: when attempting to prescriptively connect non-adjacent levels-of-organization, one must always and completely traverse each intermediary level. It is only through translation of an object or concept into the novel languages, tools, methods, and data at adjacent levels that emergent properties can be accounted for and ideas from nonadjacent levels can tentatively interact.

Levels-Of-Organization in the Learning Sciences

Once we understand that prescriptive bridges can only be meaningfully built between adjacent levels-of-organization, the reasons for the continued absence of the neuroeducation bridge become clear. Specifically, cognitive/behavioural neuroscience is separated from education by an intermediate level-of-organization: cognitive-behavioural psychology (Table 3.1). As such, the behavioural properties that emerge at the cognitive-behavioural psychology level which are required for prescriptive translation to the educational level are non-existent in, non-predictable by, and largely irrelevant to cognitive-behavioural neuroscientific research. For instance, it makes little sense to talk about 'reading' as an isolated function within cognitive-behavioural neuroscience as there is no single part of the brain that 'reads' (Dehaene, 2009). Brains, in fact, do not read – people do.

Although, it does makes sense to discuss the function and connectivity of the mechanistic foundations of reading in the brain (e.g., auditory phonemic discrimination, visual letter recognition, semantic identification, etc.), reading as a unitary, measurable, and meaningful skill only emerges as an integrated behavioural set at the cognitive-behavioural psychology level (Coch, 2010). Again, this is not to say the foundations for educationally relevant skills do not exist in the brain – but, just as speed is not a property of any individual component of a car but emerges only with the effective integration of all components, so too do larger behaviours sets emerge and obtain meaning only following cumulative integration. This is why Bruer's argument that brain science must pass through psychology in order to have incur relevance to education (at least, education as it is currently understood and practiced) is valid.

For example, cognitive-behavioural neuroscience researchers interested in mapping language to specific areas of the brain will first decompose language into its many constituent parts (e.g., verb comprehension), develop highly artificial tasks meant to isolate a single constituent part (e.g., listen to a computerized word-list consisting of 100 unrelated, context-free verbs), and indirectly measure brain activity during task performance in a highly controlled environment (for review, see Vigliocco et al., 2011). Although, it is possible to see how this type of work may influence researchers interested in determining how the constituent parts of language integrate to form a complete, emergent behavioural ‘language’ set at the cognitive-behavioural psychology level, a number of unproven assumptions must be accepted: such as that neural regions measured in isolation will behave in a similar manner when integrated with competing networks, that isolated behavioural functions will remain relatively stable when combined with secondary functions, that environmental influences will not drastically change the activation or function of specific nuclei, etc. (Chomsky, 1995).

When translating findings from cognitive-behavioural neuroscience directly to education, not only do the number and gravity of assumptions compound, but prescriptive utility evaporates. As noted, the decomposition of language, development of an artificial linguistic task, and indirect measurement of brain activity in a highly controlled environment are required in order to accomplish the goals of cognitive-behavioural neuroscientific elucidation. However, this process necessarily strips language of any meaning and ignores the influence of any competing neural and/or environmental factors: the very things one must understand in order to prescriptively influence linguistic classroom learning (Gibbons, 2002). Luckily, these factors emerge at the cognitive-behavioural psychology level with the recombination of isolated behaviours into behavioural sets and the elucidation of behavioural/environmental interactions.

For example, how does knowing that visually processing the letter “M” requires activation of neurons within the occipital lobe impact a lesson plan concerned with teaching students how to read? More important in this instance is the knowledge that reading ability is predicated upon (amongst other things) the effective integration of visual identification and phonemic discrimination: two larger behavioural sets understood and elucidated using paradigms developed at the cognitive-behavioural psychology level (Chall, 1996). Similarly, of what use is the knowledge that verb generation requires the activation of motor neurons to someone interested in helping a group of students learn how to speak French?

Again, more important in this scenario is the knowledge that learning a novel language requires (amongst other things) the integration of object recognition and conceptual mapping: two larger behavioural sets understood and elucidated using paradigms developed at the cognitive-behavioural psychology level (Barsalou et al., 2003).

Biological level	Domain	Relevant professions	Questions	Tools	Data	Example success criteria
Biosphere	State/Federal Governmental Policy	Ministers of State; Local Members of Parliament; Departmental Secretaries	What are the best long term strategies to fulfill the proposed educational and economic aims of state-mandated education?	Legislation; Policy; Government Funding, and Infrastructure	State/Nationwide Academic Achievement Patterns	Reduced Unemployment and Improved GDP
Ecosphere	District Policy	District Organizers; Denominational Board; Superintendents	What programs present the strongest cost/benefit ratio to meet the goals of district curricula?	District Policies; District Resources and Budget;	District-Wide Academic Achievement Scores/Rankings	Improved District Literacy Level Ranking
Community	Administration	Principals; Administrators; School Leaders	How can the timing and sequencing of courses across years and disciplines best meet the pedagogic and scheduling demands students, teachers, and parents?	General Curricula Programs; School Budget; School Policies	Year- and School-Wide Academic Achievement Scores/Rankings	Increased School Graduation Rates and Improved Tertiary Education Entrance
Population	Education (Practice)	Teachers; Tutors; Teaching Assistants	Which combination of integrated cognitions/behaviors and environments lead to the comprehension, memorization, and effective application of educationally relevant skills/information in a social environment?	Subject Curricula; Pedagogical Theories; Assessment Tools	Educationally Relevant Integrated Cognitions/Behaviors at the Group Level	Improved Individual and Social Employability, Well-being, and Economic Prosperity
Organism	Cognitive/Behavioral Psychology	Educational Psychologist; School Psychologist; Learning Psychologist; Cognitive/Behavioral Psychologist	How do isolated cognitions/behaviors combine to form an integrated 'set' (eg., arithmetic ability). How do these integrated behaviors develop, manifest across different scenarios, and evolve over time within an individual?	Psychometrics; Questionnaires; Cognitive Function Measures	**Integrated** Cognitions/Behaviors at the Individual Level	Elucidation of how an Individual Visually Scans and Interprets a Scene to Achieve a Pre-Established Goal
Organ	Cognitive/Behavioral Neuroscience	Cognitive Neuroscientist; Behavioral Neuroscientist	How are isolated cognitions/behaviors (eg., numerical magnitude recognition) reflected and integrated within and between neural regions?	Functional Magnetic Resonance Imaging; Scalp Electroenceph-algrophy; Transcranial Magnetic Stimulation	**Isolated** Cognitions/Behaviors and Functional Neural Networks	Localization of Primary Neural Linguistic vs. Non-Linguistic Auditory Processing Regions
Tissue	Systems Neuroscience	Systems Neuroscientist; Systems Biologist	How do neurons combine to form nuclei and how are unique nuclei organized?	Implanted Multi-Electrode Arrays; Animal Experimentation; Cell Culture	Neuronal Nuclei	Input/Output Patterns from the six Layers of the Lateral Geniculate Nuclei in response to Photostimuli
Cell	Cellular Neuroscience	Cellular Neuroscientist; Cytologist; Cellular Biologist	How do nerve cells function, communicate, and interact with unique chemical environments?	Patch-Clamps; Confocal Imaging; Laser Scanning Microscopy	Individual Neurons	Impact of Calcium Influx on Resting Action Potential Firing Rate

Several social levels could be included tangentially to the educational and proceeding levels – these were omitted for the sake of clarity. Furthermore, several levels exploring the chemical and molecular activity within cellular structures could be placed beneath the cell level – these were omitted for the sake of clarity.

Prescriptive Translation in the Learning Sciences

To see how this proposed framework leads to effective prescriptive translation in the learning sciences, it is perhaps best to start with a theoretical example. Above, we noted that evidence from cognitive-behavioural neuroscience suggests that the motor cortex demonstrates enhanced activation during verb generation (Grezes & Decety, 2001). From this, one could propose that the performance of relevant actions during novel verb generation may enhance language learning. Interestingly, this practice has been utilized in classrooms since, at least, the late 1800s – but, for our purposes, we will continue as though it were novel (Gouin, 1892). At first blush, this suggestion may appear as a valid prescriptive translation: in fact, one could easily imagine the headlines heralding this pronouncement: "Movement Activates the Brain and Improves Student Language Learning".

A closer examination, however, reveals that this is an idea which describes no constraints, parameters, or demonstrated efficacy. Although, motor cortical activation might suggest a link between movement and verb-learning, the specific type, form, content, and schedule of any relevant learning activities remains uncertain. Are all verbs and/or verb-tenses amenable to movement-based learning improvements? Would movement impact verb-learning in more complex and valid linguistic contexts? Would the interaction of multiple agents within a classroom setting impact movement practices and/or efficacy? Furthermore, each of these lingering questions – the back-bone for effective prescriptive utility (as each addresses the question of 'what to do') – ignores the most obvious unknown: does motor cortical activation even confer any impact on verb learning whatsoever?

Accordingly, rather than jump straight from neurophysiology to the classroom, prescriptive translation must first traverse cognitive-behavioural psychology, where integrated linguistic behaviours emerge and the relationship between motor cortical activation and language-learning can be systematically explored. It is here that researchers can determine how individuals come to understand verbs in context (Hamblin & Gibbs, 1999), link meaning between observed, performed, and linguistic forms of actions (Gleitman, 1990), generate novel verbs or verb-forms to shifting scenarios (Arad, 2003), etc. In other words, via cognitive-behavioural psychology, the constituent parts of language can be recombined to develop a more cohesive theory of how the integrated behavioural properties of language emerge whilst determining functional parameters for the influence of motor cortical activity on different stages of this process.

Although prescriptive utility for teachers may begin to emerge at the cognitive-behavioural psychology level, additional work undertaken at the educational level within more ecologically-valid settings is still required to account for properties that emerge when learning takes place in an ecologically-valid classroom setting. At this stage, the impact of group dynamics (Cole, 1970), inter-personal communication (Savignon, 1991), feedback (Nicholas & Lightbown, 2001), and other factors influencing the efficacy of intentional teaching and learning of a language can be determined. It is from this work that prescriptive frameworks, protocols, and/or tools can be meaningfully developed to impact teaching and learning practices (with the understanding that variations will necessarily occur according to specific classroom environments and learning goals).

Moving to a real-world example, several researchers have recently suggested that utilizing an ‘uncertain reward’ paradigm during educational activities may improve classroom learning (Howard-Jones, 2011; Ozcelik et al., 2013). These authors report that this idea springs from work done at the cognitive-behavioural neuroscience level: more specifically, it has been demonstrated that reward uncertainty leads to both an increase in dopaminergic activity within the mid-brain and enhanced anticipatory focus (Critchley et al., 2001; Fiorillo et al., 2003).

As before, although an interesting idea, these neuroscientific concepts do not confer any prescriptive actions or parameters teachers or students can utilize, nor does it guarantee efficacy at the educational level. Again, one could easily the see sensational headlines for this idea ("Uncertain Rewards Boost Dopamine and Improve Student Learning"), but emergent properties integral to education simply have not been accounted for at this stage.

Therefore, rather than jumping straight into the classroom, these researchers next incorporated ideas derived from over a century of work done at the cognitive-behavioural psychological level. It was through this body of work exploring the interplay between engagement, motivation, and risk that it became clear behaviour arising from reward uncertainty is highly influenced by goals and context. Accordingly, uncertain reward do not universally enhance engagement; rather, this works only when an individual determines the subjective context relevant risk/reward ratio is beneficial (Von Neumann & Morgenstern, 1944). Furthermore, when the importance of outcome is elevated above process, uncertain rewards reduce motivation and engagement (Shen et al., 2015).

Again, these parameters emerge only when larger behavioural sets (those non-existent in the brain as isolated functions) are explored. As stated by neuroscientist Wolfram Schulz, "There are no dedicated receptors for reward. . .[therefore] functions of reward cannot be derived entirely from physics and chemistry of input events but are based primarily on behavioural effects, and the investigation of reward functions requires behavioural theories that can conceptualize the different effects of reward on behaviour" (Schultz, 2006; p. 91).

Finally, in order to account for the properties which emerge at the educational level, these researchers moved to the classroom where they conducted a 5-stage design-based study (Howard-Jones et al., 2015). As can be expected, during this process a number of issues unpredictable and irrelevant to the cognitive-behavioural psychology level emerged: for instance, issues of cognitive load amongst teachers (divided between reward-schedules and teaching), asymmetric engagement between peer groups, and socially-driven emotional reactions. Through this work, the authors were able to iteratively design an engaging and effective learning tool: an excellent example of the prescriptive process engaging with and accounting for emergent properties at preceding levels of organization.

The Curious Case of Learning Disabilities

To date, the majority of neuroscience work commonly cited as 'successfully translated' into the educational sphere concerns learning disabilities. More specifically, the delineation of the neural mechanisms that constitute larger behavioural sets and the ability to measure functional brain activity have allowed researchers to determine the underlying pathology behind varied forms of learning difficulties. Once the underlying source of a dysfunction is localized, relevant and effective remediation can be commenced.

Although, this process may appear to be prescriptive between education and neuroscience, a closer examination reveals this to be a form of diagnostic translation (with prescriptive elements between neuroscience and psychology). More specifically, though understanding the underlying neural reasons why a student is unable to engage with a specific skill within a classroom may lead to effective remediation ideas, it does not generate any specific actions to be undertaken nor does it speak to the potential efficacy of those actions. Furthermore, the concept of 'remediation' is not the same as the concept of 'learning.' The goal of remediation is to eliminate any underlying block or barriers impeding a student's ability to engage with learning tasks – however, this process is moot on the larger process of the learning-tasks themselves. For this reason, remediation activities are typically undertaken at an individual psychological (rather than a social educational) level.

As an example, hypoactivation of both frontal and left temporal brain regions relevant for phonological processing have been implicated in dysphonetic dyslexia (Temple et al., 2001). This knowledge has led several researchers to create intervention programs that may successfully correct this abnormal neural activity (though, the parameters for these programs were necessarily elucidated, tested, and established at the psychological level (Gaab et al., 2007; Simos et al., 2002). Although this is an excellent example of prescriptive interplay between the neuropshysiological and psychological levels, it is important to note that remediation of phonological processing does not confer the ability to read. Once neural activity is more reflective of 'neurotypical' patterns, a student with learning disabilities is simply better-positioned to engage with the process of learning to read at the educational level – remediation does not obviate the need to undertake the learning process. It is correct to argue that understanding the underlying neural processes behind reading and reading disabilities can inspire more effective learning activities (beyond remediation) – however, once this process commences, the earlier discussions of prescriptive translation become relevant.

A similar pattern can be seen in work done with dyscalculia. Recently, researchers have determined that one form of dyscalculia can be driven by abnormal development of or activity within the bi-hemispheric intraparietal sulci (Price et al., 2007) – areas of the brain linked to numerosity (Castelli et al., 2006; Pinel et al., 2001).

As before, this knowledge has led to the development of intervention programs aimed at helping individuals connect quantities with the words and/or symbols that represent them (elucidated, tested, and established at the psychological level (Butterworth & Laurillard, 2010; Butterworth & Yeo, 2004). As before, these intervention programs serve to remedy an underlying issue thereby allowing a student to more effectively engage with mathematical learning activities – but it does not speak to those activities themselves. Again, it is correct to argue that understanding the mechanistic foundations of numeracy and dyscalculia can inspire more effective learning activities (beyond remediation) – however, once this process commences, the prescriptive translation framework becomes relevant.

How Does This Help Learning Science Researchers?

The largest implication of incommensurable levels-of-organization for researchers within the learning sciences is the elucidation of a clear prescriptive translational path. Over the last decade, large amounts of time and resources have been spent trying to argue for the relevance and creation of the bridge between non-adjacent levels; however, if we collectively acknowledge that this is practically and philosophically irrelevant (within all fields of science), we can re-direct this energy toward solidifying the bridges between adjacent levels. For instance, rather than attempting to deeply understand the vicissitudes of neuroscience and education, researchers interested in translation can focus their efforts, instead, on mastering neuroscience and psychology, or psychology and education: for it is between these adjacent levels that meaningful, prescriptive translation can take place.

In addition, researchers within individual levels can (and should) no longer feel pressured to prescriptively apply their work beyond adjacent levels, as this practice serves only to create overly-simplified models which may, in turn, evolve into neuromyths. As a concrete example, many cognitive-behavioural neuroscientists have attempted to draw a parallel between neuroplasticity and classroom practice (Abiola & Dhindsa, 2012; Brown & Wheatley, 1995; Sylwester, 1986). More specifically, many utilize evidence of neuronal re-wiring during post-stroke rehabilitation as an argument for the link between neuroscience and learning (Abiola & Dhindsa, 2012; Murphy & Corbett, 2009). At first blush, this argument may appear strong; however, a closer examination reveals it to be devoid of any true prescriptive value. Rehabilitation consists of the continual repetition of simple behaviours with the hopes of restoring larger behavioural sets (e.g., a post-stroke victim may repeat a list of simple nouns for weeks-on end in order to improve global linguistic function: Gresham et al., 1997).

Of importance here is the return of behavioural function: how this function is mirrored in the brain, although interesting, is of no consequence to the larger therapeutic goals. Would we consider it a failure if, after rehabilitation, a stroke victim regained language function without demonstrating neural re-wiring? Of course not. Accordingly, the relevance of rehabilitation to education is not in neuroplasticity (neuroscience); rather, it is in the knowledge that the repetition of specific behaviours can be utilized to improve larger, more integrated behavioural sets (cognitive-behavioural psychology): the neural mechanisms underpinning that rehabilitation or learning is prescriptively irrelevant and uninformative to the practitioner at this higher level.

Finally, the elucidation of levels-of-organization may also prove beneficial to the organization of science of learning labs and journals. For instance, in order to guide prescriptive translation, larger mind/brain/education labs may consider organizing space so as to ensure those researchers at adjacent levels are in more direct contact than those at a non-adjacent levels. Similarly, science of learning themed journals may opt to organize articles according to the organizational levels. This practice may help researchers and practitioners at all levels quickly and easily locate relevant articles from their own and adjacent levels.

How Does This Help Educators?

Several learning science theorists have recently argued that educators require greater neuroscientific literacy and that neuroscience should be included in pre-service training (Busso & Pollack, 2015; Dekker et al., 2012; Devonshire & Dommett, 2010). Although, knowledge of the brain is certainly exciting and may inspire some teachers to develop novel concepts or theories to explain classroom behaviour, the levels-of-organization framework reveals that prescriptive utility (what to do in the classroom) will never spring from this knowledge. As such, it should be made clear to educators that they need not understand the structure and function of the brain in order effectively perform their jobs.

Again, this is not to say knowledge of the brain is useless in the classroom setting (as it confers opportunities for conceptual, functional, and diagnostic translation) – this is merely to say that said knowledge is not required to successfully perform and evolve the duties of education. For this reason, although interested educators should certainly be encouraged to learn more about the brain (potentially supported by elective courses offered during preservice years), non-interested educators should not feel pressured into learning information that will ultimately not directly impact the essential skills and practices required to succeed in their chosen profession.

Beyond a call for neuroscientific literacy, educators are being bombarded with programs and activities designed ‘with the brain in mind’. Products such as Luminosity, IMPACT, Brainology, and CogMed are marketed as being brain-based, and educators interested in using them must concern themselves with issues of neural modularity and neuroplasticity. However, a closer look reveals that even these programs cannot avoid following a stepwise trajectory through the relevant levels-of-organization. For instance, CogMed may reorganize neuronal structures, but it does so only through the application and repetition of psychologically derived behavioural patterns. Of importance to educators is not whether these behavioural patterns scale-down to brain change, but whether they scale-up to more general, educationally relevant behavioural sets and outcomes. As such, educators need not worry about claims made regarding the 'brain-based' nature of a program; rather, they need only concern themselves with claims made regarding behavioural activities and educationally transferable outcomes of a program.

Again, some theorists argue enhanced neuroscience literacy amongst educators will help inoculate teachers against these types of programs (Goswami, 2006; Howard-Jones, 2014) – however, this remedy is short-sighted and misses the ultimate point. 'Brain-based' learning is not the first trend to sweep through education, nor will it be the last; as such, insisting teachers are proficient in the knowledge required to assess the scientific veracity of claims made by product designers will be a Sisyphean task. For instance, there is already discussion of a 'gene-based' education (Asbury & Plomin, 2014): does this mean teachers must next become literate in genetics? How about when personalized tutoring-systems emerge: much teachers then learn Artificial Intelligence algorithms? Rather than asking already overly-busy teachers to obtain more knowledge, the levels-of-organization framework clarifies that teachers need only obtain the right knowledge. In these instances, educational trends can be effectively and successfully addressed by ensuring teachers focus only on the evidence that matters most to their practice: more specifically, how does a program impact the learning of students within my particular educational setting? This inquiry makes obsolete any facts that do not take into account the emergent properties relevant to education (e.g., facts about the brain function, genetic coding, computational scripts, etc.). Furthermore, ensuring teachers focus their inquiries on practically relevant information may inspire the designers of learning products to obtain and deliver data more meaningful for their target audience.

Taking this concept further, it is conceivable that within the next decade engineers will develop a portable interface capable of measuring and analysing brain activity on the fly (indeed, many companies already advertise prototypes of such devices). Even if one were to use this interface to develop an educational program that adapts to a student's unique neural patterns, this would be as hollow as current brain-based programs. As before, in this instance, brain activity is not guiding education – it is merely guiding sets of behaviours that may scale-up to relevant educational outcomes. Again, the efficacy of this program would not be measured in brainwaves or brain change; rather, it would be measured in the transfer of the skill/s obtained via repetition of behaviours to the larger behavioural goals of education. Explicit knowledge of brain function and change does not obviate the need for proper competence, comprehension, and transfer as elucidated using behavioural measures. This becomes especially clear when one remembers that functional neural markers obtained at the cognitive-behavioural neuroscience level are necessarily reliant on the deconstruction of behaviours into constituent parts devoid of integrative meaning. Until such a time as information and skills can be directly uploaded into a student's brain (at which point, education as we currently know it will likely cease to exist) neuroscientific measures must always pass through the intermediary behavioural level in order to be prescriptively relevant to education.

A Bridge to the Future

Since Bruer first put forth his neuroeducation argument, there has been tremendous debate amongst researchers and practitioners concerning the merits of translating brain knowledge for classroom use. However, until now, very little has been done to clearly define what is meant by translation. This uncertainty, no doubt, has fuelled this debate and obfuscated attempts to determine what can and can not be meaningfully expected from a union between neuroscience and education.

Through our explication of four different types of translation, it is clear that neuroscience and education are already linked via conceptual, function, and diagnostic bridges. Through these forms of translation, dialog amongst educators is evolving, understanding of the holistic learning process is emerging, and options to measure and modulate neurophysiology within both typical and dysfunctional learners is expanding. However, it is also clear that neuroscience cannot prescribe practices within education except via psychology as this is the only means by which to elucidate and account for emergent properties at ascending levels of organization.

Once it is accepted that the prescriptive neuroscience / education bridge is a chimera, all the time, resources, and energy spent on trying to actualize it can be re-distributed to more fruitful prescriptive translational avenues: specifically, to the neuroscience : psychology and psychology : education junctions. Within this framework, any theoretical over-extension can easily be identified and qualified prior to the emergence of new neuromyths. In addition, much pressure will be removed from educators with regards to what concepts they are expected to understand and utilize within the classroom: specifically, any claim beyond behavioural enactment and measurement is irrelevant.

As with any novel scientific endeavour, it is important to establish a fundamental framework so as to beneficially guide development and application into the future. We believe the delineation of different forms of translation and explication of the brain/behaviour/classroom bridge required for effective prescriptive translation provides the strongest support as we continue to advance our work and will, ultimately, lead to faster and more successful prescriptive translation between the laboratory and the classroom.

Acknowledgement

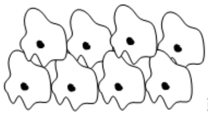
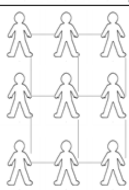
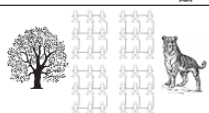
Australian Research Council – Special Research Initiative. Science of Learning Research Centre, project number SR120300015.

Post-Publication Addendum

Levels of analysis.

In order to clarify the development of the levels of analysis proposed in this paper, the following explanatory figure is provided.

Figure 2-2 *Levels of Analysis in Biological Systems.*

Level of Analysis	Graphic Depiction	Description
Cell		Consistent with Modern Cell Theory, the individual cell is the simplest form of life, qualitatively different from purely physical, non-living material.
Tissue		When a number of identical individual cells connect with each other, a tissue is formed, Often functions as a physical barrier, e.g. the arachnoid tissue in the brain.
Organ		A co-ordinated combination of different types of tissue results in an organ with a specific function. Examples include eyes, kidneys, hearts.
Individual		An individual – or person in the human species - is the result of the integration of a number of interacting systems of organs.
Population		Any group of individuals forms a population in which there is little or no interaction.
Community		When the individuals in any population and interact, communicate and co-ordinate together, a community is formed.
Ecosphere		An ecosphere is the result of a community forming interactive connections with other living entities in its local environment.
Biosphere		A biosphere is the formation of full connectivity between multiple local environments or ecospheres.

Learning disabilities: Remediation and learning.

A further clarification is also required, that of the distinction between remediation and learning. The distinction was originally discussed on pages 74-75 in the context of a discussion regarding learning disabilities. The argument proposed is that while neuroscience may inform professionals on conditions that impede a student's learning, it does not, indeed can not, prescribe how those students ought to be taught. That is to say, neuroscience cannot be prescriptive of teaching practices for students with disabilities. Should neuroscience be successful in removing that impediment to learning, this is referred to as a 'remediation' of the underlying impediment, allowing learning to occur. The remediation is *not* learning itself, it is the removal of an impediment to learning. An example would be a student who suffers from attention-deficit, and consequently is unable to learn her times-tables. In this situation, a neuroscience professional might prescribe a treatment that increases the child's attention span (that is, remediates the impediment to learning) allowing the teacher to use their standard teaching methods, uninformed by neuroscience, to enable the student to successfully learn.

Chapter 4.

Educational Neuroscience: A Systematic Review of the Literature

This chapter reports an analysis of the neuroeducation literature, in which some 548 studies are analysed using the abstracted framework from Chapter 2 and the Translation Schema from Chapter 3. The hypothesis to be tested in this study is that there will be no published study that validly prescriptively translates neuroscience into education. This chapter is an essentially unedited version of a manuscript that has been submitted to a peer-reviewed journal (Donoghue & Hattie, 2016) and which is currently under review. The candidate is the primary and lead author of this article, developed the concept, contributed 90% of the content, and was primarily responsible for the planning, execution and preparation of the work for publication.

Introduction

Chapters 2 and 3 of this thesis have described two schema by which translation of educational neuroscience and educational psychology can be validly translated into educational practice. Despite the promise and in some cases hype about the impacts that neuroscience may have on education many academics have warned against the validity of drawing conclusions about educational practice and neuroscientific findings (Hruby, 2012; Bowers, 2016; Bruer, 1997). A valid question then is ‘to what degree and in what ways has neuroscience *so far* been translated into education? The studies reported in this and the next chapter directly address that question. In this chapter, the results of a systematic review of the neuroscience literature examining the impact of neuroscience on education will be reported. In the following two chapters, a meta-analysis and meta-synthesis examining the impact of educational psychology on education will be reported. These will allow for comparison between the two disciplines.

According to the argument made in Chapter 3, the hypothesis to be tested in this chapter is that there will be no published empirical evidence of *prescriptive* translation between neuroscience and education. This hypothesis rests on the argument that incommensurability, increasing complexity of levels of organisation and the existence of emergent properties make such translation invalid and meaningless. It was further argued in that chapter that even when prescriptive translation can be made between *adjacent* layers, confirmation of that translation can only be conducted in that higher layer.

To test this hypothesis, in this chapter 548 articles were sourced and systematically analysed: first against the Abstracted Framework, and second against and the Translation Schema, in the search for any study that prescriptively translated from neuroscience into education. A second purpose of this study was to evaluate the validity and utility of both the framework ("does it allow for comprehensive and meaningful categorisation of the neuroscience and educational literature?") and the translation schema ("does it comprehensively and accurately describe the types of translation that is being conducted in the neuroscience and educational literature?").

Method

In order to test the extent and validity of translation of educational neuroscience into educational practice, three sources of published articles were identified. First, all articles with the words "neuroeducation" or "educational neuroscience" in the title, abstract or keywords were searched on Google Scholar using Publish or Perish software (Harzing, 2011; Tarma Software Research, 2016). These articles were then sorted according to the Google Scholar Index - an indicator of their impact as measured by the total number instances where the article had been cited. In an attempt to match the sample size of the MBE sample (244 articles), the top 251 Publish or Perish articles were chosen (abbreviated as "TOP") as a representative sample of published papers.

The next two sources of articles were from two dominant educational neuroscience journals in publication. The second source was every published article in the history of Trends in Neuroscience and Education (TINSE), dating back to its inception in 2012. The third and final source was every published article in the history of the peer-reviewed journal, Mind, Brain and Education (MBE), dating back to its inception in 2007.

The articles from these three sources were pooled, then examined according to the following criteria:

- Is the article duplicated – that is, was it included in two or more of the three sources?
- Is the article a book or non-peer reviewed book chapter?
- Does the article relate to the teaching *of* neuroscience to medical students or similar?
- Is the article unrelated to the application of neuroscience to education?
- Was the article published or released without peer review?
- Was the article administrative or otherwise non-academic in nature?

If the article satisfied any one of these criteria, it was eliminated from the study. Each article in the remaining pool was then analysed individually according to the Abstracted Framework and the Translation Schema. Each study was first categorised according to its *source* layer (the layer in the framework from which the study sourced its original data or conducted its experiments); second, for each study the *applied* layer was identified (the layer in the framework to which the study applied its findings), and third which of the 4 types of translation was used.

Each article was then analysed for the type of translation (if any) involved. The criteria for this decision are described in Table 4-1 below, based on the four types of translation proposed in Chapter 3.

Table 4-1. *Translation Schema Criteria.*

Translation Type	Criteria	Example
Prescriptive	Does the study specify practices to be undertaken at the educational level on the basis of evidence derived from lower layers of the Abstracted Framework?	"The middle temporal cortex lights up when a child hears their name. Therefore teachers who use students' names are more effective."
Conceptual	Does the study allow for individuals to understand or conceive of phenomena at the educational level through theories derived from lower layers of the Abstracted Framework? ?	"Learning is a biological adaptation that was naturally selected to increase our survival. Teachers may understand their craft more deeply if they focus on natural learning mechanisms."
	Does the study generate a testable hypothesis about educational application	"Memory and emotional functions are strongly linked in the brain. Therefore it is hypothesised that a student's emotional state will affect their learning."
Functional	Does the study allow for phenomena at a lower layer of the Abstracted Framework constrain behaviours and cognitions at the educational level?	"This child has a hearing impairment. Therefore s/he should be seated closer to the teacher during class."
Diagnostic	Does the study describe cognitions and/or behaviours at the educational level to be backward-mapped to and correlated with phenomena that exist at lower layers of the Abstracted Framework?	"Autism is currently measured by a behavioural test. Our study has used fMRI data to identify a neurological marker that accurately diagnoses autism without a behavioural test."
None	The study made to translation from any Layer in the Abstracted Framework into education.	Not applicable

It was hypothesised that there would be no articles in which *prescriptive* translation was used where the source layer was neuroscientific (either cellular or cerebral) and the applied layer was sociocultural.

Results

The combination of articles from the three sources created a total pool of 548 articles - 251 from TOP, 244 from MBE and 53 from TINSE, summarised in Table 4-1. All 548 articles were then individually examined and 185 were excluded from the study as follows: 28 were administrative articles (for example, the announcement of awards); 37 were book chapters or whole books; 16 articles were duplicates (that is, featured in the Top 251 and published in either TINSE or MBE); 61 were medical in nature (that is, related to the teaching *of* neuroscience for medical students); 16 were not related to the application of neuroscience to education; and finally 27 were articles had not been peer reviewed. This left a total of 363 articles to be analysed according to the framework and schema. The selection and elimination process is presented graphically in Figure 4-1, and the exclusions are summarised in Table 4-1 below.

Table 4-2. *Summary of exclusions.*

Exclusion Reason	No. of Studies
Administrative	28
Book or Book Chapter	37
Duplicate	16
Medical	61
Not Neuro-education relevant	16
Not peer reviewed	27

Total Excluded	185
Total Included	363
Grand Total	548

Figure 4-3. *Schema of exclusion process.*

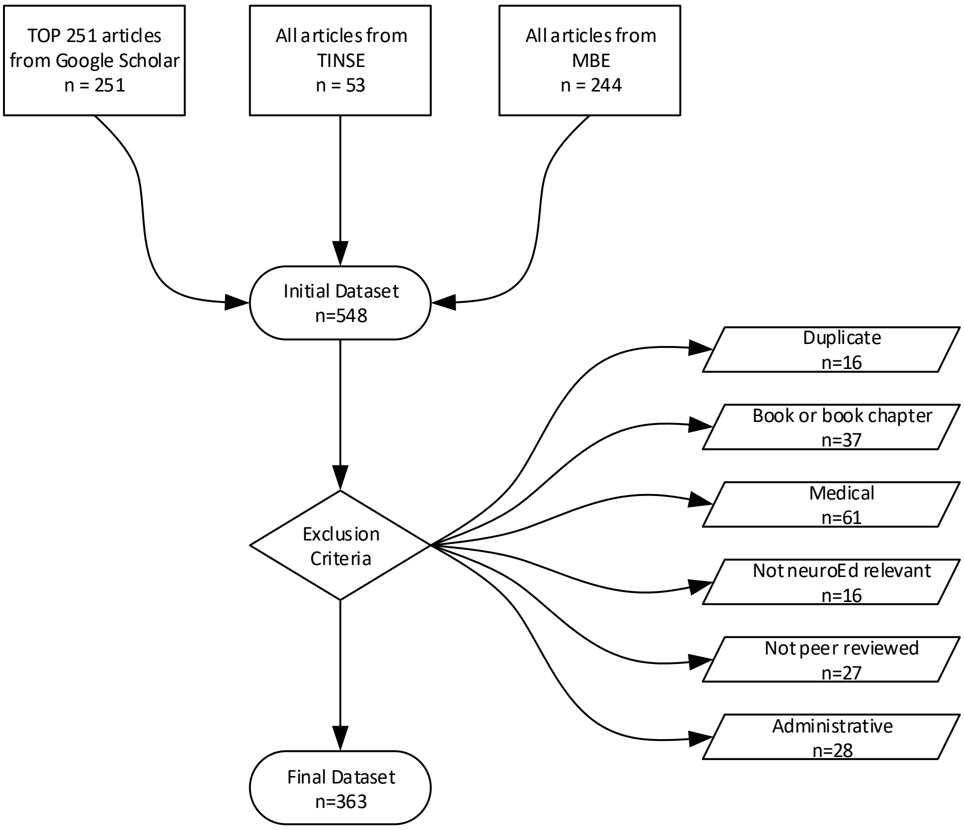


Table 4-2 summarises the number of studies, before and after the exclusion process, categorised according to each source.

Table 4-2. *Sources of studies.*

Source	No. of Studies	
	Before Exclusions	After exclusions
TOP	251	95
TINSE	53	52
MBE	244	216
Total	548	363

Each of these 363 articles was then reviewed and analysed according to the Abstracted Framework and the Translation Schema. Of the 363 studies, 157 were categorised as conceptual, 28 were diagnostic, 22 were functional, 50 were prescriptive, and 106 involved no attempts at translation.. These classifications are summarised in Table 4-3 below.

Table 4-3. *Summary of Translation Types.*

Translation Type	No of Studies
Prescriptive	50
Conceptual	157
Functional	22
Diagnostic	28
None	106
Total	363

Applicability of the model.

Every study was successfully classified into a layer in the Abstracted framework, and every study was successfully classified according to the translation schema. Notwithstanding, there were two findings that may lead to improvements in these artefacts in future research. First, in a second analysis of the literature base, an attempt was made to classify articles in the Individual layer into finer sub-categories – Individual-Behavioural and Individual-Cognitive. This was not successful, as many of the studies could not be so distinguished, so the original super-category (Individual) was retained.

Second, during the coding of the 363 studies, it was observed that some 15 articles within the Conceptual category could have been more finely categorised into one of two new sub-categories. These 15 articles were consequently tagged to this effect during the analysis: 12 were tagged in the 'Top Down' sub-category and a further 3 in the 'Hypothesis Generation sub-category'. The results reported above did not make reference to this distinction. The implications of these two incidental findings will be discussed later in this chapter.

Translations.

Of the 257 articles in which any translation was made, 157 (61.1%) were conceptual: informing educational professionals through theories and concepts from other disciplines, but without prescribing what those professionals need to do in their practice. A representative example of such conceptual translation was provided by Lieberman (2012), who cited established research that showed improvements to recall when information is 'socially encoded'. While proposing that such results could have "potentially tremendous" implications for education, he was careful in his conclusion to emphasise that his claims were conjecture, and not yet substantive. In the absence of any substantive evidence that such neurological knowledge had been prescriptively translated into educational practice, this paper, and many others like it, were categorised as Conceptual.

In total, there were 50 prescriptive translations: one paper made prescriptions into the Cerebral layer, 27 into the Individual Layer, and the remaining 22 made prescriptions into the Sociocultural layer. Of these 22 Sociocultural prescriptions, 12 translated from the Individual layer to the Sociocultural, and 10 translated from within the Sociocultural layer *to* the Sociocultural layer. One of these 10 studies (Dommett et al., 2013), prima facie, prescribed the teaching of a neuroscience curriculum in order to enhance incremental intelligence beliefs – or growth mindset (Blackwell & Dweck, 2007) - and prima facie, this could appear to be in contradiction to the current hypothesis. This specific study, and the reasons for its categorisation, will be discussed in further detail in the next section.

Discussion

The successful categorisation of every one of the 363 studies into the abstracted framework – both at the *source* and *applied* layers - lends support to the validity and applicability of the model. It indicates that the five layers of the model are sufficient and adequately discreet to distinguish between studies from the disparate disciplines. In future applications of the framework, however, it may be worthwhile to introduce sub-layers – particularly in the Individual layer where many (although not all) of the studies could be more finely categorised as Individual-behavioural or Individual-cognitive -

In contrast, however, the analysis indicated significant limitations to the translation schema. First, 12 studies explicitly took a known learning phenomenon and investigated its neural correlates (see Dawson & Stein, 2008; Grabner et al., 2012; Macedonia et al., 2010; and Masson et al., 2014; as representative examples). These 12 studies were classified as *Conceptual* in this analysis, however they are more accurately examples of a type of translation that was not incorporated into the schema: *top-down* translation. The neuro-education literature is replete with studies that implicitly assume that the goal of translation is to take scientific findings from various disciplines, and apply those findings into education – that is, the ultimate goal is *bottom-up* translation, and *prescriptive* bottom-up translation at that (Hook & Farah, 2013; Horvath & Donoghue, 2016; Pickering & Howard-Jones, 2007).

This, however need not be the case –professionals operating in the sociocultural layer (particularly educators) are more than able to inform other disciplines - and with equal authority as do those disciplines attempt to inform education. Using brain-imaging tools to identify the neural correlates of known cognitive phenomena is a common pursuit amongst neuroscientists (Ogawa et al., 1990), often without any explanation of why such investigations are important. Google Scholar for example reports over 293,000 articles with the phrase "neural correlates" in the title, abstract or keywords, with investigations into such pursuits as the neural correlates of consciousness (5,850 articles) and the neural correlates of learning (659 articles). Identifying the neural correlates of an individual's cognitive activities or predispositions in this way is a definitive example of top-down translation: translating research from a higher layer to a subordinate layer. The vast array of published articles that conduct this type of translation points to the need for including top-down as the fifth type of translation.

The predominant type of translation attempted in the reviewed studies was conceptual (61.1%). That is, the research was conducted research in Layers I, II, III or IV, and conceptual, theoretical or hypothetical extrapolations were made into the sociocultural layer. As reported, there was no study in which the source layer was Cerebral, and the applied layer Sociocultural and where the translation was prescriptive, and as such the hypothesis - that prescriptive translation between layers in the framework is not viable - has been confirmed.

There was one study, however (Dommett et al., 2013), that prima facie could have been classified as prescriptive from the Cerebral layer to the Sociocultural layer, thereby invalidating the hypothesis. Notwithstanding, categorising this study as such, while seemingly valid, is in fact not. In their study, Dommett and colleagues analysed data from 383 year 7 students, aged 11-12 years, from five schools in Gloucestershire UK, aged 11 -12 years. The students were randomly allocated into one of five intervention conditions, two experimental and three control:

- Experimental 1: students were taught neuroscience material by an Advanced Skills Teacher (AST-Neuro);

- Experimental 2: students were taught neuroscience material by an interactive computer program (Comp-Neuro);
- Control 1: students were taught study skills material by an Advanced Skills Teacher (AST-Study);
- Control 2: students were taught study skills material by an interactive computer program (Comp-Study);
- Control 3: No intervention.

The neuroscience intervention was directed towards teaching children about neuroplasticity, as the hypothesis to be tested was that students who were taught about the plasticity of the brain would be more likely to adopt a ‘growth’ mindset and that this in turn would lead to improved (maths-related) learning outcomes. The dependent variables measured across these conditions using a national standardised test and established self-report scales were:

- Maths achievement test;
- Implicit beliefs about intelligence (theory of intelligence);
- Beliefs about effort; and
- Beliefs about academic performance.

These measures were conducted before intervention (baseline), immediately after the final workshop (P1), 7 months after the final workshop (P2) and finally 19 months after the final workshop (P3). The study found that those students taught the neuroscience course showed “long-term increases of belief in incremental intelligence” (p. 127), but did not perform better in maths. In conclusion, the authors stated “neuroscience training can produce a mild but significant increase in students’ beliefs in incremental intelligence up to 19 months after training” (p. 137). Further, the authors also found that the level of neuroscience training of the expert teachers had no impact on the learning outcomes of the students (p.131) – an interesting finding given the importance other researchers have attributed to neuroscience literacy of teachers (Horvath, Lodge, Hattie & Donoghue, 2019; Howard-Jones, Franey, Mashmoushi & Liao, 2009).

While this study is a clear example of prescriptive translation (i.e. "teach a course in neuroscience and your students will show an increase in incremental intelligence beliefs") it is *not* making this prescription on the basis of evidence from the neuroscientific literature. The evidence on which this prescription is made was collected within the *Sociocultural* layer – in an experimental classroom involving teachers, students, materials, curricula and content – albeit content that was about neuroscience. To be an example of prescriptive translation from Cerebral to Sociocultural, the evidence on which the prescription is made would need to be collected from the Cerebral layer – that is, from a study in the neuroscience of learning. While Dommett et al.'s study was *about* a neuroscience curriculum, it was *not* a neuroscience study – it did not study the neurons, brains, or cognition of the students (for example, using brain-imaging tools), it studied the students in their classroom context. It is therefore a piece of educational, not neuroscientific, research, and as such does not invalidate the current hypothesis.

Concluding Remarks

The results lend support to the validity and practicality of the Abstracted Layered Framework. All articles were validly and reliably categorised into the framework, and doing so enabled meaningful analysis to inform the current hypothesis. Future applications of the framework may benefit from more finely distinguished sub-categories (for example within the Individual layer) but even in its current form, the framework has proved worthwhile.

The analysis has also pointed to two improvements in the translation schema. First, in contrast to the widely-held assumption that translation is a one-way process – from the bottom-up, this analysis has lent support to the notion that valid and worthwhile translation can be top-down as well as bottom-up. This point was not lost in Bowers' (2016) controversial paper in which he concludes that "whereas neuroscience cannot help education in the classroom, the question of how education impacts the brain is fundamental to neuroscience" (p. 2). Future applications of the schema would therefore benefit from the inclusion of a new category of "top-down" translation.

Second, many articles drew on evidence from the neuroscientific and psychological layers to generate hypotheses about what would happen in the sociocultural layer. Such articles were also categorised as conceptual – as they did not provide substantive evidence in the sociocultural layer so could not be categorised as prescriptive. Future applications of the schema would therefore benefit therefore from the inclusion of a new category of "hypothesis-generation" translation.

The results of this study supported the hypothesis – despite many examples of conceptual, diagnostic and functional translation between the layers, there was no empirical study that validly translated neuroscience into education. There was no evidence of a single classroom intervention that was prescribed on the basis of neuroscience research. Neuroscience research has conceptualised various aspects of classroom practice; it has detected neurological correlates of teaching and learning phenomena that were already well-known; and it has even generated several hypotheses that remain to be tested. Neuroscience can inform, it can explain, it can confirm, it can inspire and help conceptualise learning. Neuroscience can even be informed by education, but to date, according to these 363 studies, neuroscience has failed to prescribe any classroom practice that educational professionals did not already know. This finding raises more questions than it answers about the very nature and validity of educational neuroscience as a discipline – and it is these questions that will be addressed, albeit not resolved, in the concluding chapter of this thesis.

Post-Publication Addendum

This systematic review analysed articles published in or before 2016. Since that time, in excess of 1000 articles have been published which have met the same inclusion criteria that were used in this chapter. These articles have been ranked according to their Google Scholar ranking using Publish or Perish (Harzing, 2011; Tarma Software Research, 2016), and while a systematic review of this more recent literature is beyond the scope of this thesis, of the most highly-ranked articles three emergent themes are relevant and worthy of brief discussion.

First, and most relevant to this thesis, is the article by Bowers (2016), in which he systematically and comprehensively debunks many of the claims, on practical and theoretical grounds, that educational neuroscience will have a powerful impact on educational practice. For example, he challenges the early neuroeducational claims, such as Blakemore and Frith's (2005) prediction:

We believe that understanding the brain mechanisms that underlie learning and teaching could transform educational strategies and enable us to design educational programs that optimize learning for people of all ages and of all needs (p. 459).

Bowers concludes that the evidence shows that this (and other) predicted transformations of education have not yet materialised. Addressing this limitation, Mayer (2017) echoes Bruer's (1997; 2006; 2016) conceptual models by affirming the role of educational neuroscience as a 'linking science' (p. 835), while confirming the conclusion in this thesis that ". . . (neuroscientific) research has not yet not had much impact on education" (p. 835). Mayer's concept of positioning educational neuroscience as a linking science is not dissimilar from the framework and schema outlined in Chapters 2 and 3, and is supported by the data analyses in the current chapter.

In the same volume of the journal, Howard-Jones et al. (2016) and Gabrieli (2016) respond to Bowers' claims. A central argument is that Bowers 'misrepresent(s) the nature and aims of the work in this new field' (p. 620), and while challenging many of the principled arguments of Bower, the authors provide no empirical evidence confirming that neuroscience has had any measurable, let alone prescriptive, impact on educational practice. It is reasonable to conclude therefore, that while researchers in this field continue to debate the potential benefits of neuroscience in education, there is currently an absence of supporting empirical evidence.

Second, Dubinsky et al. (2019) reported that the teaching of neuroscience to educators had significant impacts on the teachers' knowledge of neuroscience, their understanding of neuroplasticity, and their attitudes to teaching and learning. They conclude that:

From these experiences, teachers indicate that learning neuroscience is welcomed and has positive, perhaps transformational, impact on their professional practice (p.404).

The authors' findings are similar in kind to those of Dommett et al., (2013), discussed in the current chapter above, where it was noted that such findings do not support the notion that neuroscience has prescribed any educational practice. Such an assertion does not invalidate the contention of this thesis in that it provides no evidence that neuroscience is being prescriptively translated into education. Like Dommett et al, Dubinsky et al. provide no evidence of neuroscience knowledge prescribing any type educational intervention, even if their claim regarding the change in teacher attitudes is in fact supported by their data.

Finally, there are two categories of studies that have been published in the period 2016-2019, neither of which provide an empirical challenge to the conclusions of this chapter. A number of recent articles discuss the oft-repeated claims about the inappropriateness and danger of neuromyths in education (see Bailey, Madigan, Cope & Nicholls, 2018; Grospietsch & Mayer, 2019; Horvath, et al., 2019;.McMahon, Yeh & Etchells, 2019). Whilst providing empirical evidence of the impact (or lack thereof) on education of acceptance of neuromyths, none of these articles provide any empirical evidence that educational neuroscience has been prescriptively translated into education. Similarly, the predominant discussion in other top-cited articles (see Thomas, Ansari & Knowland, 2019, for a representative review) related to assertions about the philosophy, appropriateness and/or potential of neuroeducation, but do not base their contentions on empirical data.

It is reasonable therefore to conclude, in the absence of a comprehensive, systematic review of the articles published between 2016 and 2019, there has been no published article that directly challenges the conclusions drawn in this chapter.

Chapter 5.

Educational Psychology: Learning Strategies: A Meta-analysis of Dunlosky et al. (2013)

This chapter builds on a qualitative review of learning strategies conducted by Dunlosky et al. (2013), who published a comprehensive *qualitative* review of 10 high impact and commonly-used learning strategies. Their review narrowed down the vast field of literature on the more than 400 learning strategies known in the teaching profession (see Chapter 6), however it (by design) did not provide a quantitative analysis. In this chapter, this limitation was addressed with a meta-analytic review of those 10 strategies.

We conducted a meta-analysis of their 10 learning strategies based on the data from their 399 cited references, and report the Cohen's *d* effect sizes for each strategy. Further, we analysed these strategies according to a number of moderators including learning domain, length of recall, depth and transfer of learning, and student age. The meta-analysis results were consistent with the findings of Dunlosky et al.'s qualitative ratings, but confirm that all learning strategies, including those rated as Low or Moderate, were all well in the 'effective' range of $d > .4$. Further, the moderator analysis revealed that the evidence on which Dunlosky's and the current study are based is very specific, and may not support generalized conclusions about human learning. The analysis revealed the importance of the nuances in the research, and indicates that the use of such strategies at various points in learning may need to be carefully integrated into the teaching process by way of an overarching conceptual model.

This chapter is an essentially unedited version of a manuscript submitted for publication in a peer-reviewed journal (Donoghue & Hattie, 2016). The candidate is the primary and lead author of this article, co-developed the concept, contributed 80% of the content, and was primarily responsible for the planning, execution and preparation of the work for publication.

Introduction

While the purpose of schooling may change over time and vary between jurisdictions, the mechanisms by which human learning occurs is arguably somewhat more universal. Learning strategies – actions that learners can take to enhance their own learning – have attracted considerable research interest in recent years (Alexander, 2014; Edwards, Weinstein, Goetz & O'Neil, 2014). This is unsurprising given the direct, practical applicability of such research, and its relevance to students, educators and school leaders alike, but such relevance also promises to shed light on the underlying neurological mechanisms of learning: if it can be shown that any given strategy has universal efficacy, then it arguably is deploying a property of a universal neurological learning mechanism.

A recent major, thorough, and important review of various learning strategies has created much interest. Dunlosky, Rawson, Marsh, Nathan and Willingham (2013) reviewed 10 learning strategies and a feature of their review is their careful analyses of possible moderators to the conclusions about the effectiveness of these learning strategies, such as learning conditions (e.g., study alone or in groups), student characteristics (e.g., age, ability), materials (e.g., simple concepts or problem-based analyses), and criterion tasks (e.g., different outcome measures). They grouped the 10 strategies into three groups based on whether they considered them having high, medium or low support for their effectiveness in enhancing learning. Categorised as High Support were Practice Testing (self-testing or taking practice tests on to-be-learned material) and Distributed Practice (implementing a schedule of practice that spreads out study activities over time in contrast to massed or ‘crammed’ practice). Categorised as Moderate support were Elaborative Interrogation (generating an explanation of a fact or concept), Self-Explanation (where the student explains how new information is related to already-known information) and Interleaved Practice (implementing a schedule of practice mixing different kinds of problems within a single study session). Finally, categorised as Low support were Summarization (writing summaries of to-be-learned texts), Highlighting/Underlining (marking potentially important portions of to-be-learned materials whilst reading), Keyword Mnemonic (generating keywords and mental imagery to associate verbal materials), Imagery use (attempting to form mental images of text materials while reading or listening), and Re-reading (restudying text material again after an initial reading). In a subsequent article targeted at a professional audience, Dunlosky (2013) claimed that some of these low support strategies (that students use extensively) have “failed to help students of all sorts” (p. 20), the benefits “can be short lived” (p.20), they may “not be widely applicable” (pp. 20-21), the benefits are “relatively limited” (p.21), and they do not provide “much - if any - bang for the buck” (p.21).

Practice testing is one of the two strategies with the highest utility. This must be distinguished from high stakes testing: practice testing instead involves any activity where the student practices retrieval of to-be-learned information, reproduces that information in some form, and evaluates the correctness of that reproduction against an accepted ‘correct’ answer. Any discrepancy between the produced and ‘correct’ information then forms a type of feedback that the learner can use to modify their understanding. Practice tests can include a range of activities that students can conduct on their own, such as completing questions from textbooks or previous exams, or even self-generated flashcards. According to Dunlosky et al., such testing helps increase the likelihood that target information can be retrieved from long-term memory and it helps students mentally organize information which supports better retention and test performance. This effect is strong regardless of test form (multiple choice or essay), even when the format of the practice test does not match the format of the criterion test, and it is effective for all ages of student. Practice testing works well even when it is massed, but is even more effective when it is spaced over time. It does not place high demand on time, is easy to learn to do (but some basic instruction on how to most effectively use practice tests helps), is so much better than unguided restudy, and so much more effective when there is feedback about the practice test outputs (which also enhances confidence in performance).

There has been an enormous number of studies that have shown that practice spread out over time (spaced) it much more effective than practice over a short time period (massed) – what is known as distributed practice. Most students need three to four opportunities to learn something but these learning opportunities are more effective if they are distributed over time, rather than delivered in one massed session: that is, spaced practice (not skill and drill), spread out (not crammed), and longer inter-study intervals (rather than shorter, or none), all lead to more effective learning. There have been four meta-analyses of spaced vs. massed practice involving about 300 studies, with an average effect of 0.60 (Cepeda, Pashler, Vul, Wixte & Rohrer, 2006; Donovan & Radosevich, 1999; Janiszewski, Noel & Sawyer, 2003; Lee & Genovese, 1988). The longer the spacing the greater the retention (e.g., if the student wishes to remember something for one week, spacing should be 12 to 24 hours apart, to remember for 5 years then spaced 6 to 12 months apart (Cepeda et al., 2008). Further, spaced practice is more effective for deeper than surface processing, and for all ages. The educational messages are to: review previous covered material in subsequent units of work; time tests regularly and not all at the end (which encourages cramming and massed practice); and given that students tend to rate learning higher after massed practice, to demonstrate to them the benefits of spaced practice.

Elaborative interrogation, self-explanation, and interleaved practice received moderate support. Elaborative interrogation involves asking “Why” questions - “Why does it make sense that?”, “Why is this true?”. A major purpose is to integrate new information with existing prior knowledge. The effects are higher when elaborations are precise rather than imprecise, when prior knowledge is higher than lower, and when elaborations are self-generated rather than provided, however a constraint of the method is that it is more conducive to surface than to deep understanding. Self-explanation involves students explaining some aspect of their processing during learning. It works across task domains, across ages, but may require training, and can take some time to implement. Interleaved practice involves alternating study practice of different kinds of items, problems, and even subject domains rather than blocking study. The claim is that interleaving leads to better discrimination of different kinds of problems, more attention to the actual question or problem posed, and as above there is more likelihood of spaced than mass practice. The research evidence is currently small, and it is not clear how to break tasks in an optimal manner so as to interleave them.

There is mixed and often low support, claimed Dunlosky et al., for summarization, highlighting, keyword mnemonic, imagery use for text learning, and re-reading. Summarization involves students writing summaries of to-be-learned texts with the aim of capturing the main points and excluding unimportant or repetitive material. The generality and accuracy of the summary are important moderators, and it is not clear whether it is better to summarize smaller pieces of a text (more frequent summarization) or to capture more of the text in a larger summary (less frequent summarization). Younger and less capable students are not as good at summarization, it is better when the assessments are generative or performance-based rather than closed or multiple choice tests, and it can require extensive training to be of optimal use. Highlighting and underlining are simple to use, do not require training, and demand hardly any additional time beyond the reading of the text. It is more effective when professionals do the highlighting than for the student doing the highlighting, at least for reading other students' highlights. It may be detrimental to later ability to make inferences; overall it does little to boost performance.

The keyword mnemonic involves associating some imagery with the word or concept to be learned. The method requires generating images which can be difficult for younger and less capable students, and there is evidence it may not produce durable retention. Similarly imagery use is of low utility. This method involves students mentally imaging or drawing pictures of the content using simple and clear mental images. It too is more constrained to imagery-friendly materials, and by memory capacity. Re-reading is very common. It is more effective when the re-reading is spaced and not massed, the effects seem to decrease beyond the second reading, is better for factual recall than for developing comprehension, and it is not clear it is effective with students below college age.

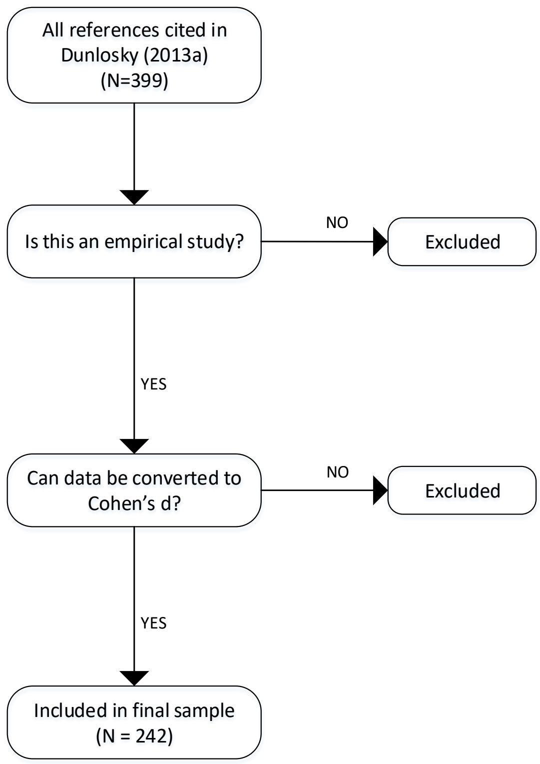
A follow-up article that was more teacher-accessible was also published by Dunlosky (2013) and asks why students do not learn about the best strategies for learning. Perhaps, he suggests, it is because curricula are developed to highlight content rather than how to effectively acquire it; and it may be because many recent textbooks used in teacher education courses fail to adequately cover the most effective strategies or how to teach students to use them. He noted that employing the best strategies will only be effective if students are motivated to use them correctly but teaching students to guide their learning of content using effective strategies will allow them to successfully learn throughout their lifetime. Some of his tips include: give a low-stakes quiz at the beginning of each class and focus on the most important material; give a cumulative exam which encourages students to restudy the most important material in a distributed fashion; encourage students to develop a ‘study planner’ so they can distribute their study throughout a class and rely less on cramming; encourage students to use practice retrieval when studying instead of passively rereading their books and notes; encourage students to elaborate on what they are reading, such as by asking “why” questions; mix up problems from earlier classes so students can practice identifying problems and their solutions; and encourage highlighting but only in the beginning of their learning journey.

There are two aspects of this research that this paper aims to address. First, Dunlosky et al. (2013) relied on a traditional literature review method and did not include any estimates of the effect-sizes of their various strategies, and nor did they indicate the magnitude of their terms high, medium, and low. One of the purposes of this article is to provide these empirical estimates. Second, Dunlosky did not empirically evaluate the moderators of the 10 learning strategies, such as deep vs. surface learning, far vs. near transfer, or age/grade level of learner. The second aim of this paper is to analyse the effects of each of the 10 strategies with respect to these and other potential moderators.

Method

Research syntheses aim to summarise past research by estimating effect-sizes from multiple, separate studies that address a specific research question. In this case, that question is what is the effectiveness of the 10 major learning strategies, and the data is based on the 399 studies referenced in Dunlosky et al. (2013). All non-empirical studies were excluded, as were studies that reported insufficient data for the calculation of a Cohen’s *d* (Cohen, 1992). This resulted in 242 studies being included in the meta-analysis, many of which contained data for multiple effect sizes, resulting in 1,619 cases for which a Cohen's *d* was calculated (see Figure 5-1).

Figure 5-1. *Schema of exclusion process.*



The publication dates of the article ranged from 1929 to 2014, with half being published since 1996. Most participants (68.4%) were adults (including graduates, and undergraduates), while 10.6 % were secondary students, 13.1% primary students, 9% from early childhood. Most were chosen from the "normal" range of abilities (94.7%), but 3.6% were called low ability and 1.7% high ability. The participants were predominantly North Americans (85.9%), and also included Europeans (12.8%), and Australians (3.2%).

All articles were coded by the two authors, and independent colleagues were asked to re-code a sample of 30 (about 10%) to estimate inter-rater reliability. This resulted in a kappa of .89, which gives much confidence in the dependability of the coding.

For each study, three sets of moderators were coded. The first set of moderators included attributes of the article: quality of the Journal (h-index), year of publication, and sample size. The second set of moderators included attributes of the students: ability level of the students (low, normal, and high), country of the study, grade levels of the student (pre and primary, high, University, and adults). The third set of moderators included attributes of the design: whether the outcome was near or far transfer (e.g., was the learner tested on a criterion tasks that differed from the training tasks or did the effect of the strategy improve the student learning in a different subject domain), the depth of the outcome (surface or content specific vs. deep or more generalizable learning), how delayed was the testing from the actual study (number of days), and the learning domain of the content of the study or measure (e.g., cognitive, non-cognitive).

The design of most studies include control-experimental (91.0%), longitudinal (pre-post, time series) 6.5%, and within subject designs (2.4%). Most learning outcomes were classified as Surface (93.3%) and the other 6.7% Deep. The post-tests were predominantly completed very soon after the intervention – 73.9% in the first week, 90.7% within the first week, while only 1.7% at 3 months or more. Table 5-6 provides full details of this moderator.

We used two major methods for calculating Cohen's *d* (Cohen, 1992) from the various statistics published in the studies. First, standardized mean differences (N=1,206 effects) involved subtracting the control group mean from the experimental group mean, and dividing this by an estimate of the pooled standard deviation.

$$Cohen's\ d = \frac{\bar{x}_e - \bar{x}_c}{SD_{pooled}} \quad where\ \ SD_{pooled} = \frac{SD_e + SD_c}{2}$$

The standard errors of these effects were calculated using:

$$SE = \sqrt{\left\{n_1 + \frac{n_1}{n_1 * n_1}\right\} + \left\{\frac{es * es}{2(n_c + n_e)}\right\}}$$

We adjusted the ES’s according to Hedge to account for bias in sample sizes, as follows:

$$ESg = es * \left\{1 - \frac{3}{(4N-9)}\right\}$$

Second, F-statistics (for two groups only – N=157 effects) were converted using

$$ES_f = \sqrt{F * \frac{\{n_c + n_e\}}{\{n_c * n_e\}}}$$

The standard errors were calculated as follows (Neyeloff, 2012):

$$SE = \frac{ES}{\sqrt{ES * N}}$$

In all cases, therefore, a positive effect meant that the learning strategy had a positive impact on learning of the to-be-learned content.

Two other methods were also used for the remaining effects - we converted published t-scores (where MSDs were not published) (N= 111) using the formula

$$ES = \frac{2 * t}{\sqrt{N}}$$

Effect sizes from one study (N=4) were converted from a reported Odds Ratio using the formula

$$ES = \frac{\sqrt{3}}{\pi} * (log_{10} OR)$$

In the remaining effects (N= 128), a Cohen’s *d* was reported, but without sufficient data to enable a manual calculation, and in these cases the published *d* was used.

The distribution of effect sizes and sample sizes was examined to determine if any were statistical outliers. Grubbs' (1950) test was applied (see also Barnett & Lewis, 1978). If outliers were identified, these values were set at the value of their next nearest neighbour. We used inverse variance weighted procedures to calculate average effect sizes across all comparisons (Borenstein, Hedges, Higgins, & Rothstein, 2005). Also, 95% confidence intervals were calculated for average effects. Possible moderators (e.g., grade level, duration of the treatment) of the DBP to student outcome relationship were tested using homogeneity analyses (Cooper et al., 2009; Hedges & Olkin, 1984). The analyses were carried out to determine whether (a) the variance in a group of individual effect sizes varies more than predicted by sampling error and/or (b) multiple groups of average effect sizes vary more than predicted by sampling error.

Rather than opt for a single model of error, we conducted the overall analyses twice, once employing fixed-error assumptions and once employing random-error assumptions (see Hedges & Vevea, 1998, for a discussion of fixed and random effects). This sensitivity analysis allowed us to examine the effects of the different assumptions (fixed or random) on the findings. If, for example, a moderator is found to be significant under a random-effects assumption but not under a fixed-effects assumption, then this suggests a limit on the generalizability of the inferences of the moderator. All statistical processes were conducted using the Comprehensive Meta-Analysis software package (Borenstein et al., 2005).

The examination of heterogeneity of the effect size distributions within each outcome category was conducted using the Q statistic and the I^2 statistic (Borenstein et al., 2005). To calculate Q and I^2, we entered the corrected effect-sizes for every case, along with the SE (calculated as above) and generated homogeneity data. Due to the substantive variability within the studies, even in the case of a non-significant Q test, when I^2 was different from zero, moderation analyses were carried out through subgroup analysis (Wilson & Lipsey, 2007). As all hypothesized moderators were operationalized as categorical variables, these analyses were performed primarily through subgroup analyses, using a mixed-effects model.

Results

Table 5-1 shows an overall summary of the analysed data. For the 242 studies, we calculated a total of 1,619 effects, which related to 178,205 participants. This large unique N value is primarily attributable to two meta-analytic studies: Donovan (1999) which reported 112 effect sizes from 63 studies with a unique N of 8,980 and Janiszewski et al. (2003) – 97 studies with a unique N of 148,979. The overall mean assuming a fixed model was 0.55 (SD = 0.81, SEM=0.072, skewness 1.3, kurtosis = 5.64); the overall mean assuming a random model was 0.56 (SE = 0.016). The overall mean at the study level was 0.77 (SE=0.049, k = 242). The fixed effects model assumes that all studies in the meta-analysis share a common true effect size, whereas the random effects model assumes that the studies were drawn from populations that differ from each other in ways that could impact on the treatment effect. Given that the means estimated under the two models are similar we proceed to use only one (the random model) in subsequent analyses.

Table 5-1. *Summary of effects for each learning strategy.*

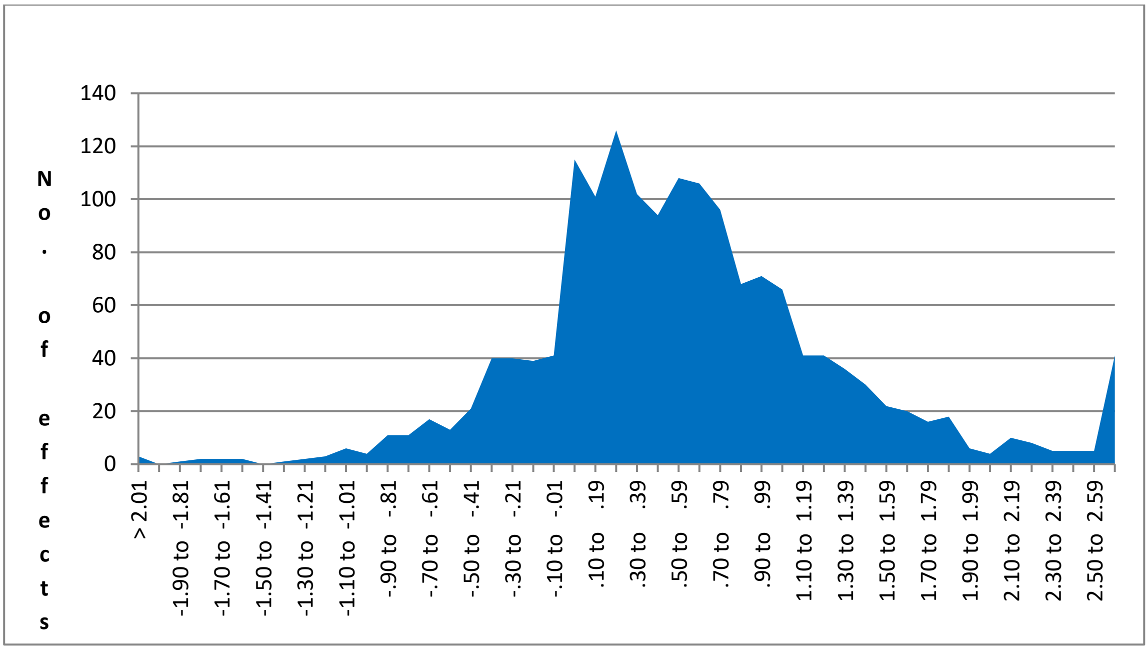
Learning Strategy	Dunlosky classification	# cases	Unique N	d	SEM	q	I^2
Distributed Practice	High	163	162,035	0.84	0.053	887.0	83%
Elaborative Interrogation	Moderate	254	2,138	0.56	0.048	1172.4	78%
Highlighting/ Underlining	Low	54	985	0.45	0.115	242.0	77%
Imagery	Moderate	135	1,052	0.56	0.061	415.9	68%

Interleaved Practice	Low	99	884	0.45	0.089	864.3	88%
Mnemonics	Low	107	580	0.50	0.104	933.9	89%
Practice Testing	High	358	6,180	0.72	0.04	2613.3	86%
Re-Reading	Low	121	1,451	0.47	0.06	792.3	86%
Self-Explanation	Moderate	93	766	0.54	0.092	394.0	77%
Summarization	Low	235	2,134	0.45	0.055	2063.4	89%
Mean/Total		1619	169,179	0.55		10,378.5	83%

Table 5-1 also shows an overall summary of effects moderated by the learning strategies. The effects correspond to the classification of High, Moderate, and Low by Dunlosky et al., but it is noted that Low is still relatively above the average of most meta-analyses in education – Hattie (2009, 2012, 2015) reported an average effect-size of .40 from over 1200 meta-analyses relating to achievement outcomes.

The distribution of all effects is presented in Figure 5-2 and every study, its attributes, and effect-size are presented in Appendix 2. It is clear that there is much variance among these effects (Q= 10,688.2, I^2=84.87). The I^2 is a measure of the degree of inconsistency in the studies' results; and this I^2 of 85% shows that most of the variability across studies is due to heterogeneity rather than chance. Thus, the search for moderators is critical to understanding which learning strategies work best in which situations.

Figure 5-2. *Distribution of effect sizes, all studies.*



Moderator Analyses

Year of publication.

There was no relation between the magnitude of the effects and the year of the study (r=0.08, df=236, p=0.25) indicating that the effects of the learning strategy have not changed over time (from 1929 to 2015).

Learning domain.

The vast majority of the evidence is based on measurements of academic achievement: 223 of the 242 studies (92.1%) and 1527 of the 1619 cases (94.3%). English or Reading was the basis for 82 of the studies (34.3%) and 532 of the cases (32.9%), Factual Recall 60 studies (25.1%) and 446 (27.5%) of the cases, and Science 41 studies (16.9%) and 336 cases (20.6%). There was considerable variation in the effect sizes of these domains.. See summary of the effect sizes of each learning domain in Table 5-2 below.

Near vs. far transfer.

If the study measured an effect on performance in the same domain as the intervention, it was rated as measuring Near transfer, alternatively it was rated as Far transfer. Of the 1,619 cases studied, 1422 (87.8%) of them measured effects on Near transfer, and only 197 (12.2%) cases of Far transfer. In all but practice testing, there was insufficient data to calculate an ES moderated by transfer so these results are not reported. In the case of practice testing, while the overall ES was *d* .= .72 (large), the effect on far transfer was even larger, *d* = .84. Caution must be applied to this finding however, given the small sample size of studies that differentiated near vs far transfer (*N* = 189, *k* = 3, *cases* = 12). Overall, the effects on Near (*d* = 0.60, SE=0.044, k = 229, cases = 1422) were very similar to the effects on Far (*d*=0.59, SE 0.207, k = 17, cases = 197).

Table 5-2. *Effect sizes moderateby by Learning Domain.*

EFFECT SIZES	English	General Knowledge	Humanities	Languages	Mathematics	Factual Recall	Science	Unknown
Elaborative Interrogation	0.38		-0.11			0.46	0.76	
Self-Explanation	0.36				0.50		0.63	
Summarization	0.39		-0.08			0.59	0.77	
Underlining	0.42		-0.19	2.16		0.52	0.50	
Mnemonics	1.17		0.00	0.75		-0.34		
Imagery	0.51		0.00	2.98		1.01	0.29	
Re-Reading	0.54		0.44				-0.04	
Practice Testing	0.94	0.52	0.70	1.29	0.13	0.71	0.64	
Distributed Practice	0.88		0.88	0.67	0.39	1.16	0.63	0.61
Interleaved Practice	0.10		0.99		1.66	0.31	0.20	
OVERALL	0.65	0.52	0.35	0.88	0.61	0.45	0.63	0.61

Blank spaces indicate insufficient data was available to calculate an Effect Size.

Depth of learning.

The effects were higher for Surface (d=0.59 , SE=.042, k = 232, cases = 1510) than for Deep processing (d=0.23, SE=0.096, k=15, cases = 109). Of all 1619 cases, 93.3% were related to surface learning.

Grade level.

The effects moderated by grade level of the participants are presented in Table 5-2 (early years and adult studies not included). Overall, there were 1054 effects measures on undergraduate tertiary students. Students of all grade levels were shown to improve learning (positive effect sizes) by using Summarization, Distributed practice, Imagery and Self-explanation. Re-reading was shown to be effective for both Primary and Tertiary students, however there was insufficient data for secondary students. Primary students had lower effects than secondary and tertiary on Interleaved practice, Mnemonics, Self-explanations, and Practice testing. Both Primary and Secondary students had lower effects on Underlining.

Table 5-3. *Effect sizes moderated by grade level.*

Strategy	Primary			Secondary			Tertiary		
	Mean	SE	Cases	Mean	SE	Cases	Mean	SE	Cases
Distributed practice	0.57	0.108	15	0.70	0.241	5	0.89	0.063	115
Elaborative Interrogation	0.38	0.136	28	0.71	0.055	84	0.58	0.094	110
Imagery	0.38	0.058	101	0.82	0.170	8	1.16	0.175	26
Interleaved practice	-0.20	0.150	13	0.00	0.066	12	0.65	0.107	79
Mnemonics	0.00	0.000	6	0.69	0.173	29	0.20	0.127	72
Practice testing	-0.25	0.563	6	0.99	0.243	22	0.80	0.044	278
Re-reading	1.33	0.257	6				0.42	0.059	107
Self-explanation	0.28	0.085	15	0.57	0.158	36	0.60	0.148	42
Summarization	1.20	0.128	25	0.75	0.144	58	0.19	0.049	151
Underlining	-0.06	0.177	10	-0.10		1	0.57	0.137	43
Total	0.42	0.047	225	0.69	0.053	255	0.59	0.026	1023

Country.

Each study was coded for the country where the study was conducted. Where that information was not made clear in the article, the first author's country of employment was used. Of the 242 studies, 186 (76.9%) were from USA, 20 (8.3%) were from Canada, 28 (11.6%) from Europe (UK, Denmark, France, Germany, Italy, Netherlands), 7 (2.9%) from Australia and 1 (0.4%) from Iran – making a total North American proportion of 206 (85.1%) – and 85.9% of the cases. The results are summarised for strategies where there are more than 10 cases. Other than the drop for Europe in Mnemonics, Interleaved practice and summarisation, there is not a significant difference in effect by country.

Table 5-4. *Effect sizes moderated by Country of first author.*

Strategy	Australia	Canada	Europe	USA	Total
Distributed practice			0.56	0.87	0.86
Elaborative Interrogation		0.76		0.27	0.56
Imagery			0.88	0.52	0.56
Interleaved practice			0.21	0.60	0.47
Mnemonics			-0.44	0.73	0.33
Practice testing	0.46		0.67	0.73	0.76
Re-reading				0.47	0.47
Self-explanation	0.72		0.57	0.38	0.54
Summarization			0.29	0.44	0.44

Ability level.

Most studies investigated the effects of learning strategies on students of normal ability (1533 or 94.7% of all cases). Across all strategies, the average effect size for high ability students was 0.085 (SE = 0.125, k = 6, cases = 28); for Low ability students was

0.43, SE = 0.246, k =13, cases = 58). The effect sizes for interleaved practice and summarization were negative for high ability students.

Delay of Recall.

Studies predominantly measured very short term effects, with the exceptions of Practice Testing, Distributed Practice and Interleaved Practice, that, by their nature, necessitated longer delay periods. Most of the studies (73.9%) measured effects within 24 hours, and it was observed that most of these were immediate – that is, within a few minutes of the intervention. In hindsight, coding of the recall delay in terms of hours would have proved valuable. No distinguishable pattern emerged from the data analysis on the length of delay. Where the delay was less than a day, the average effect size was .57 (SE = 0.023, k= 172, cases = 1103), 1 day but less than 1 week *d* = 0.60 (SE = 0.058, k = 41, cases = 213), 1 week but less than 1 month, *d* = 0.58 (SE= 0.050, k = 44, cases = 179), 1 month but less than 6 months, *d* = 0.52 (SE =0.075, k = 30, cases = 83), and finally 6 months or more, *d* = 0.58 (SE = 0.256, k = 17, cases = 40). These results are summarized in Table 5-3 below.

Table 5-5. *Effect sizes moderated by Delay of Recall.*

Delay	Cases	d	SE
Less than 1 day	1103	0.57	0.023
1 day but less than 1 week	213	0.60	0.058
1 week but less than 1 month	179	0.58	0.050
1 month but less than 6 months	83	0.52	0.076
6 months or more	40	0.58	0.256
Unspecified	1	0.46	NA
Total	1619		

Journal impact factor.

The Impact factor of the publishing journal was sourced from each journal's website. A multiple-year (usually 5-year) average h-index was provided, that was used in preference to a single (the most recent) year. Impact factors for unpublished sources, (including PhD theses) were left blank, as were other articles for which a published rating was unavailable). The average impact factor is 2.68 (SE = 3.29), which relative to journals in educational psychology indicates that the overall quality of journals is quite high. Across all 10 learning strategies, there was a moderate positive correlation between effect size and Journal Impact Factor, $r(235) = 0.24$, <.001. Thus the effect-sizes were slightly higher in the more highly cited journals.

Moderator summary.

The more impactful moderators are summarized below in Table 5-4. For each moderator, the table shows that there is one predominant variable (marked with *). Taken together, these predominant variables depict the most common or typical conceptualisation of learning implicit measured in these studies: short term factual recall of surface-level, non-transferred academic content, by North American undergraduate students of normal ability.

Table 5-6. *Summary of Variables Categorised by Moderators.*

Moderator	Variable	Cases	
		No.	% of total
Learning Domain	* Academic	1527	94.3%
	Chess	4	0.2%
	Languages	47	2.9%
	Face Naming	13	0.8%
	Vocational	14	0.9%
	Navigation	2	0.1%
	Art	8	0.5%
	Cognitive	4	0.2%
Transfer	* Near	1422	87.8%
	Far	197	12.2%
Depth of Learning	* Surface	1510	93.3%
	Deep	109	6.7%
Participant Grade Level	* Undergraduate	1054	65.1%
	Primary	212	13.1%
	Early Primary	13	0.8%
	Secondary	171	10.6%
	Late Primary - Early Secondary	84	5.2%
	Pre-Kindergarten	41	2.5%
	Adult	38	2.3%
	Graduate	6	0.4%
Country	* USA	1228	75.8%
	Canada	164	10.1%
	Germany	23	1.4%
	UK	33	2.0%
	Netherlands	99	6.1%
	Australia	51	3.2%
	Iran	1	0.1%
	France	1	0.1%
	Italy	17	1.1%
	Denmark	2	0.1%
Ability Level	* Normal	1533	94.7%
	Low	58	3.6%
	high	28	1.7%
Delay of Recall	* 1 day or less	1196	73.9%
	1 day - 6 days	272	16.8%
	7 days - 13 days	34	2.1%
	14 days -29 days	21	1.3%
	30 days - 99 days	67	4.1%
	100 days – 364 days	24	1.5%
	1 year	4	0.2%
	Unspecified	1	0.1%

** denotes the predominant variable for each moderator.*

Discussion and conclusions

The major conclusion from the meta-analysis is a confirmation of the major findings in Dunlosky et al. (2013). They rated the effects as either High, Moderate, or Low and there was considerable correspondence between their ratings and the actual effect-sizes. High was .70 and above, Moderate between .54 and .56, and Low .53 and below. This meta-analysis, however, shows the arbitrariness of these ratings, as some of the Low effects were very close in size to the Moderate. Mnemonics, re-reading, and interleaved practice were all within .04 of the Moderate category – and these strategies may have similar importance to those Dunlosky et al. classified as Moderate. Certainly they should not be dismissed as ineffective. Even the lowest learning strategies - Underlining and Summarization, both *d* =.45 - are sufficiently effective to be included in a student's toolbox of strategies.

The case for distributed practice is made in an exemplary manner in Dunlosky et al. and worth repeating here to show the case, the attention to moderators, and the development of a story as to why this method is so effective. They started by elaborating the meaning of the method. "The term distributed practice effect refers to the finding that distributing learning over time (either within a single study session or across sessions) typically benefits long-term retention more than does massing learning opportunities back-to-back or in relatively close succession" (p. 35). They then outline a classic experiment in which students learn translations of Spanish words (Bahrick, 1979) under three conditions: (i) zero spacing where learning sessions were back-to-back across six massed sessions; (ii) where practice was one day apart; and (iii) when learning was 30 days apart. Optimal retention was found when relearning was 30 days apart, then 1-day compared to 0 days spacing. This, they argue, is probably because too close practice means students do not have to work very hard to reread notes or retrieve something, they may be misled by the ease of this second task and think they know the material better than they really do, or the second learning episode benefits from any consolidation of the first trace that has already happened.

Their investigation of moderator effects show that spaced practice is effective across all conditions – different materials, different learning conditions, different student characteristics and different criterion tasks. They then showed that the optimal spacing is about 10-20% of the desired retention interval: "to remember something for one week, learning episodes should be spaced 12 to 24 hours apart; to remember something for five years, the learning episodes should be spaced 6 to 12 months apart" (p. 37). They noted that many classroom activities favour massed over spaced in that textbooks too often cluster to-be-worked problems together, there is little variation in the problems to be solved, less frequent testing encouraged cramming or massed practice, and students rate the effectiveness of massed higher than spaced practice. Overall, they rate "distributed practice as having high utility: It works across students of different ages, with a wide variety of materials, on the majority of standard laboratory measures, and over long delays. It is easy to implement (although it may require some training) and has been used successfully in a number of classroom studies" (p, 40). Such careful detail runs throughout their review, showing that Distributed Practice may have a more nuanced impact than what a meta-analysis can identify.

The strategy with the lowest overall effect was summarization. Dunlosky et al. note that it is difficult to draw general conclusions about its efficacy, it is likely a family of strategies, and should not be confused with mere copying. They noted that it is easy to learn and use, training typically helps improve the effect (but such training may need to be extensive), but suggest other strategies might better serve the students. In the more popular account of their review, Dunlosky (2013) classified summarization among the "less useful strategies" that "have not fared so well when considered with an eye toward effectiveness" (p. 19). He also noted that a critical moderator for the effectiveness of all strategies is students' motivation to use them correctly. Our meta-analysis nonetheless shows that summarization, while among the less effective of the 10 under review, still has a sufficiently high impact to be considered worthwhile in the student's arsenal of learning strategies, and with training could be among the more easier to use strategies.

One of the sobering aspects of this meta-analysis is the finding that the majority of studies are based on a narrowly-defined conceptualisation of learning. As summarized in Table 5-6 above, the overwhelming majority of studies assessed North American adults of normal ability in their ability to immediately recall surface level, near-transferred facts in academic domains. This narrow conceptualisation severely limits the generalisation of the Dunlosky et al.'s review and this meta-analysis as there may well be different learning strategies that optimise deeper, delayed and more intensive learning, requiring far transfer. The verdict is still out on the effectiveness and identification of the optimal strategies in these latter conditions. It should be noted, however, that this may be not only a criticism of the current research on learning strategies but could well be the same criticism of student experiences in most classrooms. Modern classrooms are still dominated by a preponderance of academic, factual recall, teachers asking low level questions demanding content answers, and assessments privileging surface knowledge (Tyack & Cuban, 1995). Thus the strategies may remain optimal for many current classrooms, and both our meta-analysis and Dunlosky et al.'s review are silent on the appropriateness of this bias.

The implications for teachers is not that these learning strategies should be implemented as stand-alone "learning interventions" or fostered through study skills courses. They can be used, however, within a teaching process to maximise the surface and deeper outcomes of a series of lessons. For example, practice testing is among the top two strategies but it would be a mistake to then claim that there should be more testing!

Dunlosky et al. (2013) concluded that more practice testing is better, should be spaced not massed, works with all ages, levels of ability, and across all levels of cognitive complexity. A major moderator is whether the practice tests are accompanied by feedback or not. "The advantage of practice testing with feedback over restudy is extremely robust. Practice testing with feedback also consistently outperforms practice testing alone" (p. 35). If students continue to practice wrong answers, errors or misconceptions these are then successfully learnt, become high-confidence errors, and are consolidated further under the power of feedback. It is not the frequency of testing that matters, but the skill in using practice testing to learn and consolidate knowledge and ideas.

There are still many unanswered questions that need further attention. First, there is a need to develop a more overarching model of learning strategies to place these 10 and the many other learning strategies. For example, we have developed a model that argues that various learning strategies can be optimised at certain phases of learning – from surface to deep and then to transfer, from acquiring and consolidating knowledge and understanding, and involves three inputs and outputs - knowing, dispositions, and motivations; which we call the skill, the will, and the thrill (Hattie & Donoghue, 2016, included in this thesis in Chapter 6.). Memorisation and Practice testing, for example, can be shown to be effective in the consolidating of surface knowing but not effective without first acquiring surface knowledge. Problem-based learning is relatively ineffective for promoting surface but more effective at the deeper understanding, and thus should be optimal after it has been shown students have sufficient surface knowledge to then work through problem based methods.

Second, it was noted above that the preponderance of current studies (and most likely classrooms) favour surface and near learning and care should be taken to both not generalise the results of Dunlosky et al. review or our meta-analysis to when deeper and far learning is desired. Relatedly, this review was predominantly focussed on academic, mostly factual, learning. This leaves unanswered the question of whether these strategies are equally effective in non-academic learning domains, such as vocational and physical skill learning, or in social and emotional learning. Third, it is likely, as Dunlosky et al. hint, that having a toolbox of optimal learning strategies may be most effective, but we suggest that there may need to be a higher sense of self-regulation to know when to use them. Fourth, it is likely that motivation (as noted by Dunlosky, 2013) and emotions are involved in the choosing, persistence with, and effectiveness of using the learning strategies, so attention to these matters is imperative for many students. Fifth, given the extensive and robust evidence for the efficacy of these learning strategies, an important avenue of future research may centre on the value in teaching them to both teachers and students. Can these strategies be taught, and if so, how? Need they be taught in the context of specific content? In what ways can the emerging field of educational neuroscience inform these questions, particularly in identifying universal learning mechanisms that underpin the most robust learning strategies? These are all valuable questions for future research.

Post-Publication Addendum

This review focused on 399 citations in the Dunlosky et al. (2013) review, and was designed at the time to quantify their qualitative assessments of learning strategies, rather than as a comprehensive literature review. Notwithstanding, since the review was completed there have been several noteworthy articles published. A comprehensive review of these more recent studies is beyond the scope of this thesis, however the three top-ranking learning strategies – interleaved practice, distributed practice, and practice testing – are worthy of brief mention.

In subsequent publications, Dunlosky and colleagues (Foster, Was, Rawson, & Dunlosky, 2019) have suggested that research since his 2013 paper has shown that interleaving may have higher effects than originally indicated. Brunmair and Richter (2019) published an extensive meta-analysis of interleaving, however, and reported results similar to those found in this chapter. They too investigated potential moderators, confirming that the effect size of the strategy varies significantly under the impact of those moderators. They concluded that interleaving has an overall effect of Hedge's g = .42 (k = 238, N = 8,466), compared to our results d = .45 (k = 99, N = 2138). The similarly of the effect size in such a larger study is strong confirmation of the results provided in this chapter. It is worthy of note that both of these effect sizes are considered large (Cohen, 1965, 1992; Richardson, 2011) whereas Dunlosky et al. (2013a) qualitatively assessed interleaving as low.

Using the same search criteria in this chapter, no published meta-analysis of distributed practice has been identified since 2016. Notwithstanding, the effectiveness of distributed practice continues to be strongly supported by the literature. Distributed practice is effective in memory improvement in evaluating conditioning (Richter & Gast, 2017), and its positive effect, demonstrated predominantly in evidence from USA studies, has recently been confirmed in Canadian student populations (Gagnon &Cormier, 2019). While most studies have found a large effect, others have found it has significant (but low-moderate) effect on enquiry-based learning (Svihla, Wester & Linn, 2018), confirming the findings in this chapter that studying moderators of the strategy is perhaps as informative as studying the strategy itself.

Two meta-analyses on practice testing have been published since 2016. First, Adescope, Trevisan and Sundararajan (2017) confirmed the overall effect of practice testing at g = .74 (N = 15,427, k = 272), confirming – with a much larger sample size –

the results from this chapter - *d* = .72 (*N* = 6,180, *k* = 358). Second, Pan and Rickard (2018) investigated the effect of practice-testing on the *transfer* of learning, finding an overall effect of *d* = .40 (from 67 studies, *k = 192).* In contrast, this chapter reported an overall effect size of *d* = .72, and an even higher effect (*d* = .84, *k* = 12) for far transfer. As noted earlier, given the small sample size, this finding must be treated cautiously. Pan and Rickard's results confirms our findings regarding the overall effect of practice testing, but challenges the finding that its effect on transfer is stronger.

Finally, the most recent review of interleaved learning was published in 2019 by Brunmair and Richter. They found results consistent with the results published in this chapter – the effect size of interleaving ranged from .Hedges' *g* = 0.34 to *g* = 0.67 with an average of *g* = 0.42. Brunmair and Richter (2009) studied different moderator effects, namely the effect of similarity between categories of interleaved learning – a moderator not measured in this chapter.

Overall, it is reasonable to conclude that while the effect of moderators is both important and significant in learning strategy research, the evidence-base for it is small in size and limited in scope, indicating the need for more comprehensive research.

Chapter 6.

Educational Psychology: A Meta-synthesis and Conceptual Model of Learning Strategies

The analyses conducted in Chapters 4 and 5 revealed important limitations to the valid translation of science into education. While educational psychology has had a long and robust history of translation into educational practice, its impact has been confined to a specific type of learning – centred around academic achievement. In contrast, Chapter 4 demonstrated that despite significant optimism, there has not to date been any prescriptive translation from neuroscience into educational practice. The arguments set out in Chapters 2 and 3 support the position that such prescriptive translation is not possible, and that conceptual translation will be more useful, and rely on a conceptual framework.

Accordingly, this chapter seeks to expand the analysis of educational psychology: is there evidence from educational psychology that is not constrained to this narrow focus on academic achievement? If so, can this evidence be used to create a conceptual framework or model of learning?

To achieve this, a meta-synthesis was conducted in which 228 meta-analyses involving 18,956 studies, 11,006,839 students and 302 effects were empirically evaluated. It was found that despite the preponderance of constrained evidence (that is, surface level, non-transfer, short term recall, academic achievement, etc), there is sufficient evidence to support the proposal of a predictive model of learning. Such a model can categorise strategies in two dimensions. First, learning can be dimensioned in time – from acquisition, to consolidation phases, and second, it can be dimensioned in depth – from surface, to deep to transfer.

This meta-analysis chapter was first published in a peer reviewed journal (Hattie & Donoghue, 2016) and the remainder of this chapter is a substantially unchanged version of that peer-reviewed paper. The candidate is the primary author of this article, co-developed the concept, contributed 60% of the content, and was primarily responsible for the planning, execution and preparation of the work for publication.

Introduction

The purpose of this article is to explore a model of learning that proposes that various learning strategies are powerful at certain stages in the learning cycle. The model describes three inputs and outcomes (skill, will and thrill), success criteria, three phases of learning (surface, deep and transfer) and an acquiring and consolidation phase within each of the surface and deep phases. A synthesis of 228 meta-analyses led to the identification of the most effective strategies. The results indicate that there is a subset of strategies that are effective, but this effectiveness depends on the phase of the model in which they are implemented. Further, it is best not to run separate sessions on learning strategies but to embed the various strategies within the content of the subject, to be clearer about developing both surface and deep learning, and promoting their associated optimal strategies and to teach the skills of transfer of learning. The article concludes with a discussion of questions raised by the model that need further research.

There has been a long debate about the purpose of schooling. These debates include claims that schooling is about passing on core notions of humanity and civilisation (or at least one's own society's view of these matters). They include claims that schooling should prepare students to live pragmatically and immediately in their current environment, should prepare students for the work force, should equip students to live independently, to participate in the life of their community, to learn to ‘give back’, to develop personal growth (Widdowson et al., 2014).

In the past 30 years, however, the emphasis in many western systems of education has been more on enhancing academic achievement - in domains such as reading, mathematics, and science - as the primary purpose of schooling (Biesta, 2015). Such an emphasis has led to curricula being increasingly based on achievement in a few privileged domains, and ‘great’ students are deemed those who attain high levels of proficiency in these narrow domains.

This has led to many countries aiming to be in the top echelon of worldwide achievement measures in a narrow range of subjects; for example, achievement measures such as PISA (tests of 15-year olds in mathematics, reading and science, across 65 countries in 2012) or PIRLS (Year-5 tests of mathematics, reading and science, across 57 countries in 2011). Indeed, within most school systems there is a plethora of achievement tests; many countries have introduced accountability pressures based on high levels of testing of achievement; and communities typically value high achievement or levels of knowledge (Trohler et al., 2014). The mantra underpinning these claims has been cast in terms of what students know and are able to do; the curriculum is compartmentalised into various disciplines of achievement; and students, teachers, parents and policy makers talk in terms of success in these achievement domains.

Despite the recent emphasis on achievement, the day-to-day focus of schools has always been on learning - how to know, how to know more efficiently and how to know more effectively. The underlying philosophy is more about what students are now ready to learn, how their learning can be enabled, and increasing the ‘how to learn’ proficiencies of students. In this scenario, the purpose of schooling is to equip students with learning strategies, or the skills of learning how to learn. Of course, learning and achievement are not dichotomous; they are related (Soderstrom & Bjork, 2015). Through growth in learning in specific domains comes achievement and from achievement there can be much learning. The question in this article relates to identifying the most effective strategies for learning.

In our search, we identified over 400 learning strategies: that is, those processes that learners use to enhance their own learning. Many were relabelled versions of others, some were minor modifications of others, but there remained many contenders purported to be powerful learning strategies. Such strategies help the learner structure his or her thinking so as to plan, set goals and monitor progress, make adjustments, and evaluate the process of learning and the outcomes. These strategies can be categorised in many ways according to various taxonomies and classifications (e.g., Boekaerts, 1997; Mayer, 2008, Pressley, 2002; and Weinstein & Mayer, 1986). Boekaerts (1997) for example, argued for three types of learning strategies:

- cognitive strategies such as elaboration, to deepen the understanding of the domain studied;
- metacognitive strategies such as planning, to regulate the learning process; and
- motivational strategies such as self-efficacy, to motivate oneself to engage in learning.

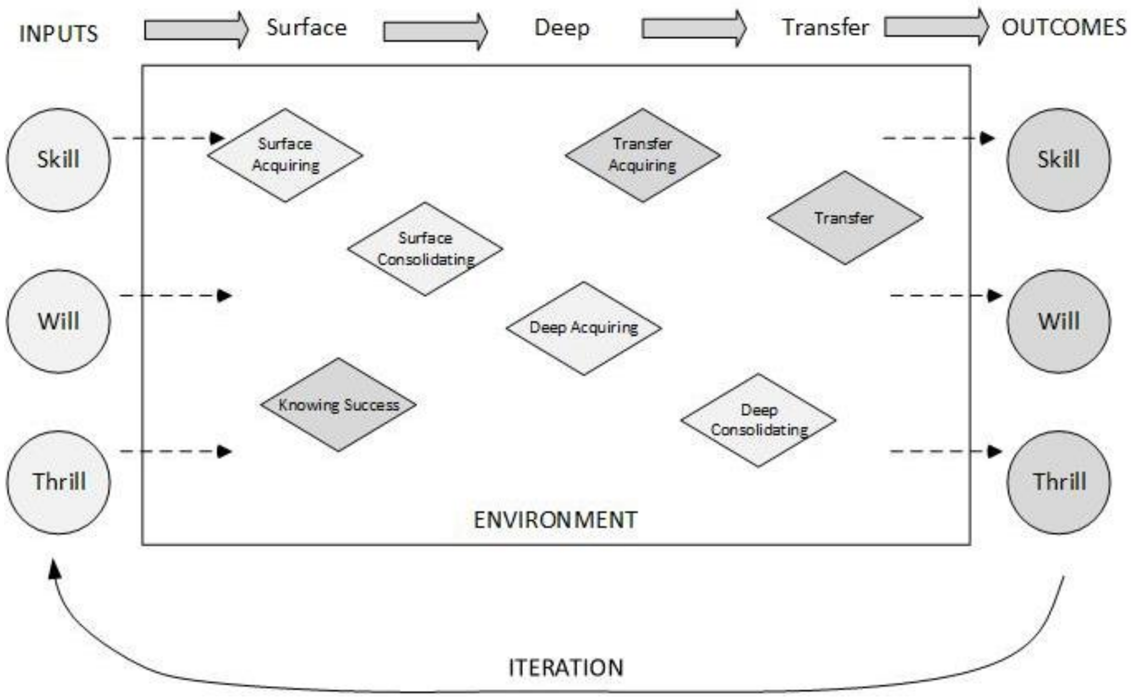
Given the advent of newer ways to access information (e.g., the internet) and the mountain of information now at students' fingertips, it is appropriate that Dignath, Buettner and Langfeldt (2008) added a fourth category - management strategies such as finding, navigating, and evaluating resources.

But merely investigating these 400-plus strategies as if they were independent is not defensible. Thus, we begin with the development of a model of learning to provide a basis for interpreting the evidence from our meta-synthesis. The argument is that learning strategies can most effectively enhance performance when they are matched to the requirements of tasks (cf. Pressley et al., 1989).

A Model Of Learning

The model comprises the following components: three inputs and three outcomes; student knowledge of the success criteria for the task; three phases of the learning process (surface, deep and transfer), with surface and deep learning each comprising an acquisition phase and a consolidation phase; and an environment for the learning (Figure 6-1). We are proposing that various learning strategies are differentially effective depending on the degree to which the students are aware of the criteria of success, on the phases of learning process in which the strategies are used, and on whether the student is acquiring or consolidating their understanding. The following provides an overview of the components of the model (see Hattie, 2014 for a more detailed explanation of the model).

Figure 6-1. *A model of learning.*



Input And Outcomes

The model starts with three major sources of inputs: the skill, the will and the thrill. The 'skill' is the student's prior or subsequent achievement, the 'will' relates to the student's various dispositions towards learning, and the 'thrill' refers to the motivations held by the student. In our model, these inputs are also the major outcomes of learning. That is, developing outcomes in achievement (skill) is as valuable as enhancing the dispositions towards learning (will) and as valuable as inviting students to reinvest more into their mastery of learning (thrill or motivations).

The skill.

The first component describes the prior achievement the student brings to the task. As Ausubel, Novak and Hanesian (1968) claimed: "If I had to reduce all of educational psychology to just one principle, I would say this "The most important single factor influencing learning is what the learner already knows. Ascertain this and teach him accordingly." Other influences related to the skills students bring to learning include their working memory, beliefs, encouragement and expectations from the student's cultural background and home.

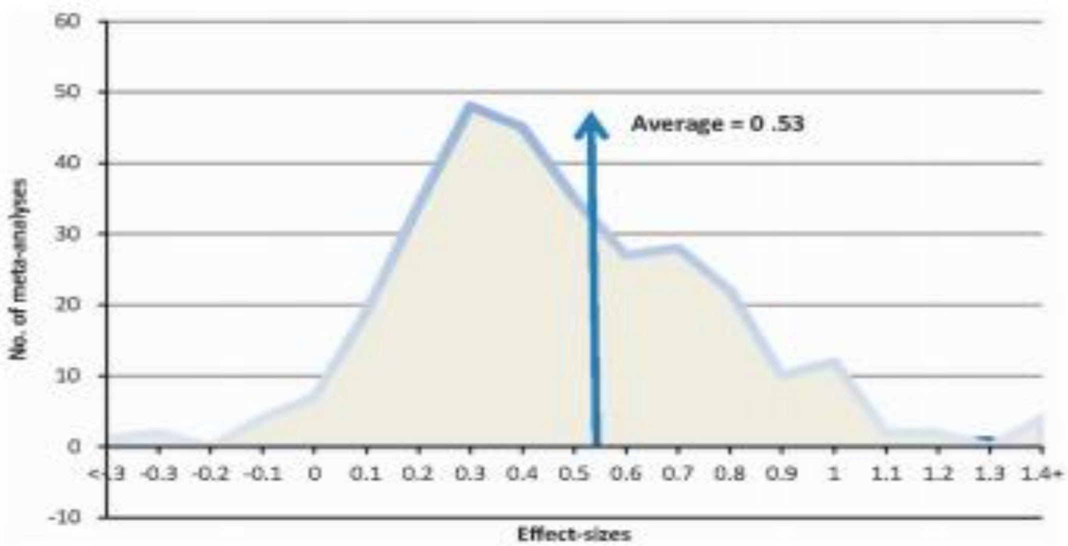
The will.

Dispositions are more habits of mind or tendencies to respond to situations in certain ways. Claxton (2013) claimed that the mind frame of a 'powerful learner' is based on the four major dispositions: resilience or emotional strength, resourcefulness or cognitive capabilities, reflection or strategic awareness, and relating or social sophistication. These dispositions involve the proficiency to edit, select, adapt and respond to the environment in a recurrent, characteristic manner (Carr & Claxton, 2002). But dispositions alone are not enough. Perkins et al. (1993) outlined a model with three psychological components which must be present in order to spark dispositional behaviour: sensitivity - the perception of the appropriateness of a particular behaviour; inclination - the felt impetus toward a behaviour; and ability - the basic capacity and confidence to follow through with the behaviour.

The thrill.

There can be a thrill in learning but for many students, learning in some domains can be dull, uninviting and boring. There is a huge literature on various motivational aspects of learning, and a smaller literature on how the more effective motivational aspects can be taught. A typical demarcation is between mastery and performance orientations. Mastery goals are seen as being associated with intellectual development, the acquisition of knowledge and new skills, investment of greater effort, and higher-order cognitive strategies and learning outcomes (Anderman & Patrick, 2012). Performance goals, on the other hand, have a focus on outperforming others or completing tasks to please others. A further distinction has been made between approach and avoidance performance goals (Elliot, & Harackiewicz, 1996; Middleton & Midgley, 1997; Skaalvik, 1997). The correlations of mastery and performance goals with achievement, however, are not as high as many have claimed. A recent meta-analysis found 48 studies relating goals to achievement (based on 12,466 students), and the overall correlation was 0.12 for mastery and 0.05 for performance goals on outcomes (Carpenter 2007). Similarly, Hulleman et al. (2010) reviewed 249 studies (N = 91,087) and found an overall correlation between mastery goal and outcomes of 0.05 and performance goals and outcomes of 0.14. These are small effects and show the relatively low importance of these motivational attributes in relation to academic achievement.

Figure 6-2. *The average and distribution of all effect sizes.*



An alternative model of motivation is based on Biggs (1993) learning processes model, which combines motivation (why the student wants to study the task) and their related strategies (how the student approaches the task). He outlined three common approaches to learning: deep, surface and achieving. When students are taking a deep strategy, they aim to develop understanding and make sense of what they are learning, and create meaning and make ideas their own. This means they focus on the meaning of what they are learning, aim to develop their own understanding, relate ideas together and make connections with previous experiences, ask themselves questions about what they are learning, discuss their ideas with others and compare different perspectives. When students are taking a surface strategy, they aim to reproduce information and learn the facts and ideas - with little recourse to seeing relations or connections between ideas. When students are using an achieving strategy, they use a 'minimax' notion - minimum amount of effort for maximum return in terms of passing tests, complying with instructions, and operating strategically to meet a desired grade. It is the achieving strategy that seems most related to school outcomes.

Success criteria.

The model includes a pre-learning phase relating to whether the students are aware of the criteria of success in the learning task. This phase is less about whether the student desires to attain the target of the learning (which is more about motivation), but whether he or she understands what it means to be successful at the task at hand. When a student is aware of what it means to be successful before undertaking the task, this awareness leads to more goal-directed behaviours. Students who can articulate or are taught these success criteria are more likely to be strategic in their choice of learning strategies, more likely to enjoy the thrill of success in learning, and more likely to reinvest in attaining even more success criteria.

Success criteria can be taught (Clarke, 2005; Heritage, 2007). Teachers can help students understand the criteria used for judging the students' work, and thus teachers need to be clear about the criteria used to determine whether the learning intentions have been successfully achieved. Too often students may know the learning intention, but do not how the teacher is going to judge their performance, or how the teacher knows when or whether students have been successful (Boekaerts, 1999). The success criteria need to be as clear and specific as possible (at surface, deep, or transfer level) as this enables the teacher (and learner) to monitor progress throughout the lesson to make sure students understand and, as far as possible, attain the intended notions of success. Learning strategies that help students get an overview of what success looks like include planning and prediction, having intentions to implement goals, setting standards for judgement success, advance organisers, high levels of commitment to achieve success, and knowing about worked examples of what success looks like (Clarke, 2005).

Environment.

Underlying all components in the model is the environment in which the student is studying. Many books and internet sites on study skills claim that it is important to attend to various features of the environment such as a quiet room, no music or television, high levels of social support, giving students control over their learning, allowing students to study at preferred times of the day and ensuring sufficient sleep and exercise.

The Three Phases Of Learning: Surface, Deep And Transfer

The model highlights the importance of both surface and deep learning and does not privilege one over the other, but rather insists that both are critical. Although the model does seem to imply an order, it must be noted that these are fuzzy distinctions (surface and deep learning can be accomplished simultaneously), but it is useful to separate them to identify the most effective learning strategies. More often than not, a student must have sufficient surface knowledge before moving to deep learning and then to the transfer of these understandings. As Entwistle (1976) noted, ‘The verb ‘to learn’ takes the accusative’; that is, it only makes sense to analyse learning in relation to the subject or content area and the particular piece of work towards which the learning is directed, and also the context within which the learning takes place. The key debate, therefore, is whether the learning is directed content that is meaningful to the student, as this will directly affect student dispositions, in particular a student’s motivation to learn and willingness to reinvest in their learning.

A most powerful model to illustrate this distinction between surface and deep is the structure of observed learning outcomes, or SOLO (Biggs & Collis, 1982; Hattie & Brown, 2004), as discussed above. The model has four levels: unistructural, multistructural, relational and extended abstract. A unistructural intervention is based on teaching or learning one idea, such as coaching one algorithm, training in underlining, using a mnemonic or anxiety reduction. The essential feature is that this idea alone is the focus, independent of the context or its adaption to or modification by content. A multistructural intervention involves a range of independent strategies or procedures, but without integrating or orchestration as to the individual differences or demands of content or context (such as teaching time management, note taking and setting goals with no attention to any strategic or higher-order understandings of these many techniques). Relational interventions involve bringing together these various multistructural ideas, and seeing patterns; it can involve the strategies of self-monitoring and self-regulation. Extended abstract interventions aim at far transfer (transfer between contexts that, initially, appear remote to one another) such that they produce structural changes in an individual’s cognitive functioning to the point where autonomous or independent learning can occur. The first two levels (one then many ideas) refer to developing surface knowing and the latter two levels (relate and extend) refer to developing deeper knowing. The parallel in learning strategies is that surface learning refers to studying without much reflecting on either purpose or strategy, learning many ideas without necessarily relating them and memorising facts and procedures routinely. Deep learning refers to seeking meaning, relating and extending ideas, looking for patterns and underlying principles, checking evidence and relating it to conclusions, examining arguments cautiously and critically, and becoming actively interested in course content (see Entwistle, 2000).

Our model also makes a distinction between first acquiring knowledge and then consolidating it. During the acquisition phase, information from a teacher or instructional materials is attended to by the student and this is taken into short-term memory. During the consolidation phase, a learner then needs to actively process and rehearse the material as this increases the likelihood of moving that knowledge to longer-term memory. At both phases there can be a retrieval process, which involves transferring the knowing and understanding from long-term memory back into short-term working memory (Mayer, 2014; Robertson et al., 2004).

Acquiring surface learning.

In their meta-analysis of various interventions, Hattie et al.(1996) found that many learning strategies were highly effective in enhancing reproductive performances (surface learning) for virtually all students. Surface learning includes subject matter vocabulary, the content of the lesson and knowing much more. Strategies include record keeping, summarisation, underlining and highlighting, note taking, mnemonics, outlining and transforming, organising notes, training working memory, and imagery.

Consolidating surface learning.

Once a student has begun to develop surface knowing it is then important to encode it in a manner such that it can retrieved at later appropriate moments. This encoding involves two groups of learning strategies: the first develops storage strength (the degree to which a memory is durably established or 'well learned') and the second develops strategies that develop retrieval strength (the degree to which a memory is accessible at a given point in time) (Bjork & Bjork, 1992). 'Encoding' strategies are aimed to develop both, but with a particular emphasis on developing retrieval strength (Bjork et al., 2007). Both groups of strategies invoke an investment in learning, and this involves 'the tendency to seek out, engage in, enjoy and continuously pursue opportunities for effortful cognitive activity (von Stumm et al., 2011). Although some may not 'enjoy' this phase, it does involve a willingness to practice, to be curious and to explore again, and a willingness to tolerate ambiguity and uncertainty during this investment phase. In turn, this requires sufficient metacognition and a calibrated sense of progress towards the desired learning outcomes. Strategies include practice testing, spaced versus mass practice, teaching test taking, interleaved practice, rehearsal, maximising effort, help seeking, time on task, reviewing records, learning how to receive feedback and deliberate practice (i.e., practice with help of an expert, or receiving feedback during practice).

Acquiring deep learning.

Students who have high levels of awareness, control or strategic choice of multiple strategies are often referred to as 'self-regulated' or having high levels of metacognition. In Visible Learning, Hattie (2009) described these self-regulated students as 'becoming like teachers', as they had a repertoire of strategies to apply when their current strategy was not working, and they had clear conceptions of what success on the task looked like (Purdie & Hattie, 2002). More technically, Pintrich et al. (2000) described self-regulation as ‘an active, constructive process whereby learners set goals for their learning and then attempt to monitor, regulate and control their cognition, motivation and behaviour, guided and constrained by their goals and the contextual features in the environment’. These students know the what, where, who, when and why of learning, and the how, when and why to use which learning strategies Schraw & Dennison, 1994). They know what to do when they do not know what to do. Self-regulation strategies include elaboration and organisation, strategy monitoring, concept mapping, metacognitive strategies, self-regulation and elaborative interrogation.

Consolidating deep learning.

Once a student has acquired surface and deep learning to the extent that it becomes part of their repertoire of skills and strategies, we may claim that they have ‘automatised’ such learning - and in many senses this automatisation becomes an ‘idea’, and so the cycle continues from surface idea to deeper knowing that then becomes a surface idea, and so on (Pegg & Tall, 2010). There is a series of learning strategies that develop the learner’s proficiency to consolidate deeper thinking and to be more strategic about learning. These include self-verbalisation, self-questioning, self-monitoring, self-explanation, self-verbalising the steps in a problem, seeking help from peers and peer tutoring, collaborative learning, evaluation and reflection, problem solving and critical thinking techniques.

Transfer.

There are skills involved in transferring knowledge and understanding from one situation to a new situation. Indeed, some have considered that successful transfer could be thought as synonymous with learning (Perkins & Salomon, 2012; Smedlund, 1953). There are many distinctions relating to transfer: near and far transfer (Barnett & Ceci, 2002), low and high transfer (Salomon & Perkins, 1989), transfer to new situations and problem solving transfer (Mayer, 2008), and positive and negative transfer (Osgood, 1949). Transfer is a dynamic, not static, process that requires learners to actively choose and evaluate strategies, consider resources and surface information, and, when available, to receive or seek feedback to enhance these adaptive skills. Reciprocal teaching is one program specifically aiming to teach these skills; for example, Bereiter and Scardamalia (2014) have developed programs in the teaching of transfer in writing, where students are taught to identify goals, improve and elaborate existing ideas, strive for idea cohesion, present their ideas to groups and think aloud about how they might proceed.

Similarly, Schoenfeld (1992) outlined a problem-solving approach to mathematics that involves the transfer of skills and knowledge from one situation to another. Marton (2006) argued that transfer occurs when the learner learns strategies that apply in a certain situation such that they are enabled to do the same thing in another situation when they realise that the second situation resembles (or is perceived to resemble) the first situation. He claimed that not only sameness, similarity, or identity might connect situations to each other, but also small differences might connect them as well. Learning how to detect such differences is critical for the transfer of learning. As Heraclitus claimed, no two experiences are identical; you do not step into the same river twice.

Overall messages from the model

There are four main messages to be taken from the model. First, if the success criteria is the retention of accurate detail (surface learning) then lower-level learning strategies will be more effective than higher-level strategies. However, if the intention is to help students understand context (deeper learning) with a view to applying it in a new context (transfer), then higher level strategies are also needed. An explicit assumption is that higher level thinking requires a sufficient corpus of lower level surface knowledge to be effective - one cannot move straight to higher level thinking (e.g., problem solving and creative thought) without sufficient level of content knowledge. Second, the model proposes that when students are made aware of the nature of success for the task, they are more likely to be more involved in investing in the strategies to attain this target. Third, transfer is a major outcome of learning and is more likely to occur if students are taught how to detect similarities and differences between one situation and a new situation before they try to transfer their learning to the new situation. Hence, not one strategy may necessarily be best for all purposes. Fourth, the model also suggests that students can be advantaged when strategy training is taught with an understanding of the conditions under which the strategy best works - when and under what circumstance it is most appropriate.

The current study

The current study synthesises the many studies that have related various learning strategies to outcomes. This study only pertains to achievement outcomes (skill, in the model of learning); further work is needed to identify the strategies that optimise the dispositions (will) and the motivation (thrill) outcomes. The studies synthesised here are from four sources. First, there are the meta-analyses among the 1,200 meta-analyses in Visible Learning that relate to strategies for learning (Hattie, 2009, 2012 & 2015). Second, there is the meta-analysis conducted by Lavery (2008) on 223 effect-sizes derived from 31 studies relating to self-regulated learning interventions. The third source is two major meta-analyses by a Dutch team of various learning strategies, especially self-regulation. And the fourth is a meta-analysis conducted by Donoghue & Hattie (2015) based on a previous analysis by Dunlosky et al. (2013) (see Chapter 5).

The data in *Visible Learning* (Hattie, 2009) is based on 800 meta-analyses relating influences from the home, school, teacher, curriculum and teaching methods to academic achievement. Since its publication in 2009, the number of meta-analyses now exceeds 1,200, and those influences specific to learning strategies are retained in the present study. Lavery (2008) identified 14 different learning strategies and the overall effect was .46 - with greater effects for organising and transforming (i.e., deliberate rearrangement of instructional materials to improve learning, d = .85) and self-consequences (i.e., student expectation of rewards or punishment for success or failure, d = .70). The lowest effects were for imagery (i.e., creating or recalling vivid mental images to assist learning, d = .44) and environmental restructuring (i.e., efforts to select or arrange the physical setting to make learning easier, d = .22). She concluded that the higher effects involved 'teaching techniques' and related to more 'deep learning strategies', such as organising and transforming, self-consequences, self-instruction, self-evaluation, help-seeking, keeping records, rehearsing/memorising, reviewing and goal-setting. The lower ranked strategies were more 'surface learning strategies', such as time management and environmental restructuring.

Of the two meta-analyses conducted by the Dutch team, the first study, by Dignath et al. (2008) analysed 357 effects from 74 studies (N = 8,619). They found an overall effect of 0.73 from teaching methods of self-regulation. The effects were large for achievement (elementary school, .68; high school, .71), mathematics (.96, 1.21), reading and writing (.44, 0.55), strategy use (.72, .79) and motivation (.75, .92). In the second study, Donker et al. (2013) reviewed 180 effects from 58 studies relating to self-regulation training, reporting an overall effect of .73 in science, 0.66 in mathematics and 0.36 in reading comprehension. The most effective strategies were cognitive strategies (rehearsal 1.39, organisation .81 and elaboration .75), metacognitive strategies (planning .80, monitoring .71 and evaluation .75) and management strategies (effort .77, peer tutoring .83, environment .59 and metacognitive knowledge .97). Performance was almost always improved by a combination of strategies, as was metacognitive knowledge. This led to their conclusion that students should not only be taught which strategies to use and how to apply them (declarative knowledge or factual knowledge) but also when (procedural or how to use the strategies) and why to use them (conditional knowledge or knowing when to use a strategy).

Donoghue & Hattie (2015) conducted a meta-analysis based on the articles referenced in Dunlosky et al. (2013) (see Chapter 5). They reviewed 10 learning strategies and a feature of their review is a careful analysis of possible moderators to the conclusions about the effectiveness of these learning strategies, such as learning conditions (e.g., study alone or in groups), student characteristics (e.g., age, ability), materials (e.g., simple concepts to problem-based analyses) and criterion tasks (different outcome measures).

In the current study, we independently assigned all strategies to the various parts of the model - this was a straightforward process, and the few minor disagreements were resolved by mutual agreement.

Results: the meta-synthesis of learning strategies

A summary of all effect sizes is presented in Appendix 4. There are 302 effects derived from the 228 meta-analyses from the above four sources that have related some form of learning strategy to an achievement outcome. Most are experimental -

control studies or pre - post studies, whereas some are correlations (N = 37). There are 18,956 studies (although some may overlap across meta-analyses). Only 125 meta-analyses reported the sample size (N = 11,006,839), but if the average (excluding the outlier 7 million from one meta-analysis) is used for the missing sample sizes, the best estimate of sample size is between 13 and 20 million students.

The average effect is 0.53 but there is considerable variance (Figure 6-2), and the overall number of meta-analyses, studies, number of people (where provided), effects and average effect sizes for the various phases of the model are provided in Table 6.1. The effects are lowest for management of the environment and 'thrill' (motivation), and highest for developing success criteria across the learning phases. The variance is sufficiently large, however, that it is important to look at specific strategies within each phase of the model.

Synthesis Of The Input Phases Of The Model

The inputs: Skills.

There are nine meta-analyses that have investigated the relation between prior achievement and subsequent achievement, and not surprisingly these relations are high (Table 6.2). The average effect-size is .77 (SE = .10), which translates to a correlation of .36 - substantial for any single variable. The effects of prior achievement are lowest in the early years, and highest from high school to university. One of the purposes of school, however, is to identify those students who are underperforming relative to their abilities and thus to not merely accept prior achievement as destiny. The other important skill is working memory - which relates to the amount of information that can be retained in short-term working memory when engaged in processing, learning, comprehension, problem solving or goal-directed thinking (Cowan, 2012).

Table 6-1. *Overall summary statistics for the learning strategies synthesis.*

Strategy	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Skill	13	3,371	136,270	229,370	9,572	0.75
Will	28	1,304	1,468,335	1,601,335	5,081	0.48
Thrill – motivation	23	1,468	451,899	638,099	4,478	0.34
Managing the environment	24	1,056	157,712	330,612	3,928	0.17
Success Criteria	41	3,395	57,850	416,950	5,176	0.55
Acquiring surface learning	26	935	26.656	226,156	2,156	0.63
Consolidating surface learning	71	3,366	7,296,722	7,921,822	6,216	0.57
Acquiring deep learning	14	1,066	1,314,618	1,367,818	2,582	0.57
Consolidating deep learning	58	2,885	96,776	602,176	7,196	0.53
Transfer	3	110		39,900	173	1.09
Total	**301**	**18,956**	**11,006,839**	**13,374,239**	**46,558**	**0.53**

Working memory is strongly related to a person's ability to reason with novel information (i.e. general fluid intelligence, see Ackerman et al., 2005).

Table 6-2. *Meta-synthesis results for 'the skill'.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Prior Achievement	9	3,155	113,814	193,614	8,014	0.77
Working Memory	4	216	22,456	35,756	1,558	0.68

The inputs: Will.

There are 28 meta-analyses related to the dispositions of learning from 1,304 studies and the average effect size is .48 (SE = .09; Table 6.3). The effect of self-efficacy is highest (*d* = .90), followed by increasing the perceived value of the task (*d* = .46), reducing anxiety (*d* = .45) and enhancing the attitude to the content (*d* = .35). Teachers could profitably increase students' levels of confidence and efficacy to tackle difficult problems; not only does this increase the probability of subsequent learning but it can also help reduce students' levels of anxiety. It is worth noting the major movement in the anxiety and stress literature in the 1980s moved from a preoccupation on understanding levels of stress to providing coping strategies - and these strategies were powerful mediators in whether people coped or not (Freydenberg & Lewis, 2015). Similarly in learning, it is less the levels of anxiety and stress but the development of coping strategies to deal with anxiety and stress. These strategies include being taught to effectively regulate negative emotions (Galla & Wood, 2012); increasing self-efficacy, which relates to developing the students conviction in their own competence to attain desired outcomes (Bandura, 1997); focusing on the positive skills already developed; increasing social support and help seeking; reducing self-blame; and learning to cope with error and making mistakes (Frydenberg, 2010). Increasing coping strategies to deal with anxiety and promoting confidence to tackle difficult and challenging learning tasks frees up essential cognitive resources required for academic work.

There has been much discussion about students having growth - or incremental - mindsets (human attributes are malleable not fixed) rather than fixed mindsets where attributes are fixed and invariant (Dweck, 2012). However, the evidence in Table 6-3 (d = .19) shows how difficult it is to change to growth mindsets, which should not be surprising as many students work in a world of schools dominated by fixed notions - high achievement, ability groups, and peer comparison.

Table 6-3. *Meta-synthesis results for 'the will'.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Self-efficacy	5	140	27,062	53,662	143	0.90
Task value	1	6		13,300	6	0.46
Reducing anxiety	8	247	105,370	158,570	1,305	0.45
Self-concept	6	440	345,455	372,055	2,548	0.41
Attitude to content	4	320	957,609	970,909	782	0.35
Mindfulness	3	66	4,622	4,622	184	0.29
Incremental vs entity thinking	1	85	28,217	28,217	113	0.19

The inputs: Thrill.

The thrill relates to the motivation for learning: what is the purpose or approach to learning that the student adopts? Having a surface or performance approach motivation (learning to merely pass tests or for short-term gains) or mastery goals is not conducive to maximising learning, whereas having a deep or achieving approach or motivation is helpful (Table 6-4). A possible reason why mastery goals are not successful is that too often the outcomes of tasks and assessments are at the surface level and having mastery goals with no strategic sense of when to maximise them can be counter-productive (Watkins & Hattie, 1985). Having goals, per se, is worthwhile - and this relates back to the general principle of having notions of what success looks like before investing in the learning. The first step is to teach students to have goals relating to their upcoming work, preferably the appropriate mix of achieving and deep goals, ensure the goals are appropriately challenging and then encourage students to have specific intentions to achieve these goals. Teaching students that success can then be attributed to their effort and investment can help cement this power of goal setting, alongside deliberate teaching.

Table 6-4. *Meta-synthesis results for 'the thrill'.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Deep motivation	1	72		13,300	72	0.75
Achieving approach	1	95		13,300	95	0.70
Deep approach	1	38		13,300	38	0.63
Goals (Mastery, performance, social)	11	587	348,346	401,546	3,584	0.48
Mastery goals (general)	3	158	12,466	39.066	163	0.19
Achieving motivation	1	18		13,300	18	0.18
Surface/performance approach	2	344	91,087	104,387	344	0.11
Surface/performance motivation	3	156		39,900	164	-0.19

The environment.

Despite the inordinate attention, particularly by parents, on structuring the environment as a precondition for effective study, such effects are generally relatively small (Table 6-5). It seems to make no difference if there is background music, a sense of control over learning, the time of day to study, the degree of social support or the use of exercise. Given that most students receive sufficient sleep and exercise, it is perhaps not surprising that these are low effects; of course, extreme sleep or food deprivation may have marked effects.

Table 6-5. *Meta-synthesis results for the environment.*

Management of the environment	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Environmental structuring	2	10		26,600	10	0.41
Time management	2	86		26,600	86	0.40
Exercise	8	397	30,206	96,706	2,344	0.26
Social support	1	33	12,366	12,366	33	0.12
Time of day to study	3	267	31,229	44,529	1,155	0.12
Student control over learning	4	124	7,993	34,593	161	0.02
Background music	1	43	3,104	3,104	43	-0.04
Sleep	3	96	72,814	86,114	96	-0.05

Knowing the success criteria.

A prediction from the model of learning is that when students learn how to gain an overall picture of what is to be learnt, have an understanding of the success criteria for the lessons to come and are somewhat clear at the outset about what it means to master the lessons, then their subsequent learning is maximised. The overall effect across the 31 meta-analyses is .54, with the greatest effects relating to providing students with success criteria, planning and prediction, having intentions to implement goals, setting standards for self-judgements and the difficulty of goals (Table 6-6). All these learning strategies allow students to see the 'whole' or the gestalt of what is targeted to learn before starting the series of lessons. It thus provides a 'coat hanger' on which surface-level knowledge can be organised. When a teacher provides students with a concept map, for example, the effect on student learning is very low; but in contrast, when teachers work together with students to develop a concept map, the effect is much higher. It is the working with students to develop the main ideas, and to show the relations between these ideas to allow students to see higher-order notions, that influences learning. Thus, when students begin learning of the ideas, they can begin to know how these ideas relate to each other, how the ideas are meant to form higher order notions, and how they can begin to have some control or self-regulation on the relation between the ideas.

Synthesis Of The Learning Phases Of The Model

Acquiring surface learning.

There are many strategies, such as organising, summarising, underlining, note taking and mnemonics that can help students master the surface knowledge (Table 6-7). These strategies can be deliberately taught, and indeed may be the only set of strategies that can be taught irrespective of the content. However, it may be that for some of these strategies, the impact is likely to be higher if they are taught within each content domain, as some of the skills (such as highlighting, note taking and summarising) may require specific ideas germane to the content being studied.

Table 6-6. *Meta-synthesis results for Success Criteria.*

Knowing success criteria	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Success criteria	1	7		13,300	7	1.13
Planning and prediction	4	399		53,200	420	.76
Goal intentions	2	81	8461	21,761	190	.68
Concept mapping	9	1,049	9279	75,779	1,141	.64
Setting standards for self-judgement	1	156		13,300	156	.62
Goal difficulty	7	428	30,521	57,121	526	.57
Advance organisers	12	935	3,905	136,905	2,291	.42
Goal commitment	3	257	2,360	28,960	266	.37
Worked examples	2	83	3,324	16,624	179	.37

While it appears that training working memory can have reasonable effects (*d* = .53) there is less evidence that training working memory transfers into substantial gains in academic attainment (Turley-Ames & Whitfield, 2003). There are many emerging and popular computer games that aim to increase working memory. For example, CogMed is a computer set of adaptive routines that is intended to be used 30–40 min a day for 25 days. A recent meta-analysis by the commercial owners (Owen et al., 2010) found average effect-sizes (across 43 studies) exceeding .70, but in a separate meta-analysis of 21 studies on the longer term effects of CogMed, there was zero evidence of transfer to subjects such as mathematics or reading (Melby-Lervåg & Hulme, 2013). Although there were large effects in the short term, they found that these gains were not maintained at follow up (about 9 months later) and no evidence to support the claim that working memory training produces generalised gains to the other skills that have been investigated (verbal ability, word decoding or arithmetic) even when assessment takes place immediately after training. For the most robust studies, the effect of transfer is zero. It may be better to reduce working memory demands in the classroom (Alloway, 2006).

Table 6-7. *Meta-synthesis results for acquiring surface learning.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Strategy – prior knowledge	1	10		13,300	12	0.93
Outlining & transforming	1	89		13,300	89	0.85
Mnemonics	4	80	4,705	31,305	171	0.76
Working memory training	4	191	11,854	25,154	1,006	0.72
Summarisation	2	70	1,914	15,214	207	0.66
Organising	3	104		39,900	104	0.60
Record keeping	2	177		26,600	177	0.54
Underlining & Highlighting	1	16	2,070	2,070	44	0.50
Note taking	7	186	5,122	58,322	287	0.50
Imagery	1	12	991	991	59	0.45

Consolidating surface learning.

The investment of effort and deliberate practice is critical at this consolidation phase, as are the abilities to listen, seek and interpret the feedback that is provided (Table 6-8). At this consolidation phase, the task is to review and practice (or overlearn) the material. Such investment is more valuable if it is spaced over time rather than massed. Rehearsal and memorisation is valuable - but note that memorisation is not so worthwhile at the acquisition phase. The difficult task is to make this investment in learning worthwhile, to make adjustments to the rehearsal as it progresses in light of high levels of feedback, and not engage in drill and practice. These strategies relating to consolidating learning are heavily dependent on the student's proficiency to invest time on task wisely (Claessens et al., 2010), to practice and learn from this practice and to overlearn such that the learning is more readily available in working memory for the deeper understanding.

Table 6-8. *Meta-synthesis results for consolidating surface learning.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Deliberate practice	3	161	13,689	13,689	258	0.77
Effort	1	15		13,300	15	0.77
Rehearsal & memorisation	3	132		39,900	132	0.73
Giving/receiving feedback	28	1,413	75,279	288,079	2,219	0.71
Spaces vs Massed Practice	4	360	14,811	54,711	965	0.60
Help seeking	1	62		13,300	62	0.60
Time on task	8	254	28,034	121,134	300	0.54
Reviewing records	1	8	523	523	84	0.49
Practice testing	10	674	7,147,625	7,227,425	1,598	0.44
Teaching test taking & coaching	11	275	15,772	148,772	372	0.27
Interleaved practice	1	12	989	989	65	0.21

Acquiring deeper learning.

Nearly all the strategies at this phase are powerful in enhancing learning (Table 6-9). The ability to elaborate and organise, monitor the uses of the learning strategies, and have a variety of metacognitive strategies are the critical determinants of success at this phase of learning. A major purpose is for the student to deliberately activate prior knowledge and then make relations and extensions beyond what they have learned at the surface phase.

Table 6-9. *Meta-synthesis results for acquiring deep-learning.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Elaboration and organisation	1	50		13,300	50	0.75
Strategy monitoring	1	81		13,300	81	0.71
Meta-cognitive strategies	5	355	1,203,024	1,216,324	781	0.61
Self-regulation	6	556	109,444	109,444	1,506	0.52
Elaborative interrogation	1	24	2,150	15,450	164	0.42

Consolidating deep learning.

At this phase, the power of working with others is most apparent (Table 6-10). This involves skills in seeking help from others, listening to others in discussion and developing strategies to ‘speak’ the language of learning. It is through such listening and speaking about their learning that students and teachers realise what they do deeply know, what they do not know and where they are struggling to find relations and extensions. An important strategy is when students become teachers of others and learn from peers, as this involves high levels of regulation, monitoring, anticipation and listening to their impact on the learner. There has been much research confirming that teaching help-seeking strategies is successful, but how this strategy then works in classrooms is more complex. Teachers have to welcome students seeking help, and there needs to be knowledgeable others (e.g., peers) from whom to seek the help - too often students left in unsupported environments can seek and gain incorrect help and not know the help is incorrect (Nuthall, 2007). Ryan and Shin (2011) also distinguished between adaptive help seeking (seeking help from others, such as an explanation, a hint, or an example, that would further learning and promote independent problem solving in the future) and expedient help seeking (seeking help that expedites task completion, such as help that provides the answer and is not focused on learning). They showed that adaptive help seeking from peers declines and expedient help seeking increases during early adolescence. Further, increases in expedient help seeking were associated with declines in achievement but changes in adaptive help seeking were unrelated to achievement. The key is for teachers to teach adaptive help seeking, to ensure the help is dependable and correct and to see this more of a student than a teacher skill. Help seeking needs to be welcomed before it can have an effect.

Transfer.

The transfer model promoted by Marton (2006; see also Marton, Wen & Wong, (2005) seems to be supported in that a key in teaching for transfer involves understanding the patterns, similarities and differences in the transfer before applying the strategies to new task (Table 6-11). Marton argued that transfer occurs when students learn strategies that apply in a certain situation such that they are enabled to do the same thing in another situation to the degree that they realise how the second situation does (or does not) resemble the first situation. It is learning to detect differences and similarities that is the key that leads to transfer of learning.

Table 6-10. *Meta-synthesis results for consolidating deep-learning.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Seeking help from peers	1	21		13,300	21	0.83
Classroom discussion	1	42		13,300	42	0.82
Evaluation and reflection	1	54		13,300	54	0.75
Self-consequences	1	75		13,300	75	0.70
Problem solving teaching	11	11	15,235	121,635	1,820	0.68
Self-verbalisation and self-questioning	4	226	6,196	19,496	2,300	0.64
Becoming a teacher (peer tutor)	15	839	18,193	164,493	1,272	0.54
Self-explanation	1	8	533	533	69	0.50
Self-monitoring	1	154		13,300	2,300	0.45
Self-verbalising steps in problem	3	154		39,900	154	0.41
Collaborative / Cooperative learning	18	512	35,921	168,921	1,074	0.38
Critical thinking techniques	1	117	20,698	20,698	161	0.34

Table 6-11. *Meta-synthesis results for Transfer.*

Skill	No of Metas	No of Studies	No of People	Pro-rata No of People	No of effects	ES
Similarities & differences	1	51		13,300	51	1.32
Seeing patterns to new situations	1	6		13,300	6	1.14
Far transfer	1	53		13,300	116	0.80

Discussion and Conclusions

There is much debate about the optimal strategies of learning, and indeed we identified over 400 terms used to describe these strategies. Our initial aim was to rank the various strategies in terms of their effectiveness but this soon was abandoned. There was too much variability in the effectiveness of most strategies depending on when they were used during the learning process, and thus we developed the model of learning presented in this article. Like all models, it is a conjecture, it aims to say much and it is falsifiable. The efficacy of any model can be seen as an expression of its capacity to generate a scalable solution to a problem or need in ways that resolve more issues than prevailing theories or approaches (Kuhn, 1962). The model posits that learning must be embedded in some content (something worth knowing) and thus the current claims about developing 21st century skills sui generis are most misleading. These skills often are promoted as content free and are able to be developed in separate courses (e.g., critical thinking, resilience). Our model, however, suggests that such skills are likely to be best developed relative to some content. There is no need to develop learning strategy courses, or teach the various strategies outside the context of the content. Instead, the strategies should be an integral part of the teaching and learning process, and can be taught within this process.

The model includes three major inputs and outcomes. These relate to what the students bring to the learning encounter (skill), their dispositions about learning (will) and their motivations towards the task (thrill). The first set of strategies relate to teaching students the standards for what is to be learned (the success criteria). We propose that effective learning strategies will be different depending on the phase of the learning - the strategies will be different when a student is first acquiring the matters to be learnt compared with when the student is embedding or consolidating this learning. That is, the strategies are differentially effective depending on whether the learning intention is surface learning (the content), deep learning (the relations between content) or the transfer of the skills to new situations or tasks. In many ways this demarcation is arbitrary (but not capricious) and more experimental research is needed to explore these conjectures.

Further, the model is presented as linear whereas there is often much overlap in the various phases. For example, to learn subject matter (surface) deeply (i.e., to encode in memory) is helped by exploring and understanding its meaning; success criteria can have a mix of surface and deep and even demonstrate the transfer to other (real world) situations; and often deep learning necessitates returning to acquire specific surface level vocabulary and understanding. In some cases, there can be multiple overlapping processes. A reviewer provided a clear example: in learning that the internal angles of a quadrilateral add up to 360°, this might involve surface learning, which then requires rehearsal to consolidate, some self-questioning to apply, some detection of similarities to then work out what the internal angles of a hexagon might be, and spotting similarities to the triangle rule. There may be no easy way to know the right moment, or no easy demarcation of the various phases. The proposal in this chapter is but a 'model' to help clarify the various phases of learning, and in many real world situations there can be considerable overlap.

We have derived six sets of propositions from our conceptual model of learning and the results of our meta-synthesis of research on learning strategies. The first set relates to the differential role played by what students bring to and take from the learning encounter - the inputs and outcomes. Second, there are some strategies that are more effective than others - but their relative effectiveness depends on the phase in the model of learning in which they take place. Third is the distinction between surface learning, deep learning and the transfer of learning. The fourth set relates to the skills of transfer, the fifth to how the model of learning can be used to resolve some unexpected findings about the effectiveness of some strategies, and the sixth set discusses the question 'what is learning?'.

The intertwining role of skill, will, and thrill.

Our first set of claims relates to the differential role of what students bring to and take from the learning encounter. Rather than arguing that many factors contribute to achievement (an important but sometimes the only privileged outcome of learning), we are promoting the notion that the skill, will and thrill can intertwine during learning and that these three inputs are also important outcomes of learning - the aim is to enhance the will (e.g., the willingness to reinvest in more and deeper learning), the thrill (e.g., the emotions associated with successful learning, the curiosity and the willingness to explore what one does not know) and the skills (e.g., the content and the deeper understanding). The relation between the thrill, will and skill can vary depending on the student and the requirements of the task. Certainly, negative emotions, such as those induced by fear, anxiety, and stress can directly and negatively affect learning and memory. Such negative emotions block learning: 'If the student is faced with sources of stress in an educational context which go beyond the positive challenge threshold - for instance, aggressive teachers, bullying students or incomprehensible learning materials whether books or computers - it triggers fear and cognitive function is negatively affected (CERI, 2008). Our argument is that learning can lead to enhanced skills, dispositions, motivations and excitements that can be reinvested in learning, and can lead to students setting higher standards for their success criteria. When skill, will, and thrill overlap, this should be considered a bonus; developing each is a worthwhile outcome of schooling in its own right.

It is all in the timing.

Our second set of claims is that while it is possible to nominate the top 10 learning strategies the more critical conclusion is that the optimal strategies depend on where in the learning cycle the student is located. This strategic skill in using the strategies at the right moment is akin to the message in the Kenny Rogers song - you need to 'know when to hold 'em, know when to fold 'em'. For example, when starting a teaching sequence, it is most important to be concerned that students have confidence they can understand the lessons, see value in the lessons and are not overly anxious about their skills to be mastered. Providing them early on with an overview of what successful learning in the lessons will look like (knowing the success criteria) will help them reduce their anxiety, increase their motivation, and build both surface and deeper understandings.

To acquire surface learning, it is worthwhile knowing how to summarise, outline and relate the learning to prior achievement; and then to consolidate this learning by engaging in deliberate practice, rehearsing over time and learning how to seek and receive feedback to modify this effort. To acquire deep understanding requires the strategies of planning and evaluation and learning to monitor the use of one's learning strategies; and then to consolidate deep understanding calls on the strategy of self-talk, self-evaluation and self-questioning and seeking help from peers. Such consolidation requires the learner to think aloud, learn the 'language of thinking' (Zohar, 2012), know how to seek help, self-question and work through the consequences of the next steps in learning. To transfer learning to new situations involves knowing how to detect similarities and differences between the old and the new problem or situations.

We recommend that these strategies are developed by embedding them into the cycle of teaching rather than by running separate sessions, such as 'how to learn' or study skills courses. There is a disappointing history of educational programs aimed at teaching students how to learn (Mayer, 2014; Lockhead & Clement, 1979; Mayer, 1997). Wiliam (2014) made this case for why teaching these learning strategies (e.g., critical thinking) out of context is unlikely to develop a generic skill applicable to many subjects. He noted that in a 'mathematics proof, critical thinking might involve ensuring that each step follows from the previous one (e.g., by checking that there has not been a division by zero). In reading a historical account, critical thinking might involve considering the author of the account, the potential biases and limitations that the author may be bringing to the account, and what other knowledge the reader has about the events being described. The important point here is that although there is some commonality between the processes in mathematics and history, they are not the same. Developing a capacity for critical thinking in history does not make one better at critical thinking in mathematics.

For all of the apparent similarities, critical thinking in history and critical thinking in mathematics are different, and they are developed in different ways. Many others have noted that metacognition is not knowledge-free but needs to be taught in the context of the individual subject areas (Donovan & Bransford, 2005; Vye et al., 1998). Perkins (2014) also noted that there is a certain art to infusing the teaching of thinking into content learning. Sometimes, “teachers think it is enough simply to establish a generally thoughtful atmosphere in a classroom, with regular expectations for thinking critically and creatively . . . teaching for know-how about learning to learn is a much more time-consuming enterprise than teaching for just learning the ideas. Building active know-how requires much more attention”. (Perkins, 2014; p. 215)

Another aspect to consider is the difference, identified in the model, between being first exposed to learning and the consolidation of this learning. This distinction is far from novel. Shuell (1990) for example, distinguished between initial, intermediate, and final phases of learning. In the initial phase, the students can encounter a ‘large array of facts and pieces of information that are more-or-less isolated conceptually... ‘there appears to be little more than a wasteland with few landmarks to guide the traveller on his or her journey towards understanding and mastery’ (p. 541). Students can use existing schema to make sense of this new information, or can be guided to have more appropriate schema (and thus experience early stages of concept learning and relation between ideas) otherwise the information may remain as isolated facts, or be linked erroneously to previous understandings. At the intermediate phase, the learner begins to see similarities and relationships among these seemingly conceptually isolated pieces of information. ‘The fog continues to lift but still has not burnt off completely’ (p. 542). During the final phase, the knowledge structure becomes well integrated and functions more autonomously, and the emphasis is more on performance or exhibiting the outcome of learning.

Horses for courses: matching strategies with phases.

The third set of claims relates to the distinction between surface, deep, and transfer of learning. Although not a hard and fast set of demarcations, surface learning refers more to the content and underlying skills; deep learning to the relationships between, and extensions of, ideas; and transfer to the proficiency to apply learning to new problems and situations. During the surface learning phase, an aim is to assist students to overlearn certain ideas and thus reduce the needs of their working memory to work with these new facts when moving into the deeper understanding phase. Note, for example, that Marton et al. (2005) made an important distinction between memorising without understanding first and called this rote memorisation (which has long term effect), and memorisation when you have understood and called this meaningful memorisation (which can be powerful). The evidence in the current study supports this distinction. It is when students have much information, or many seemingly unrelated ideas, that the learning strategies for the deep phase are optimally invoked. This is when they should be asked to integrate ideas with previous schema or modify their previous schema to integrate new ideas and ways of thinking. The key to this process is first gaining ideas - a fact often missed by those advocating deeper thinking strategies when they try to teach these skills prior to developing sufficient knowledge within the content domain. The students need to first have ideas before they can relate them. The model does not propose discarding the teaching or learning skills that have been developed to learn surface knowing, but advocates the benefits of a more appropriate balance of surface and deeper strategies and skills that then lead to transfer. The correct balance of surface to deep learning depends on the demands of the task. It is likely that more emphasis on surface strategies is probably needed as students learn new ideas, moving to an emphasis on deeper strategies as they become more proficient.

Pause and reflect: detecting similarities and differences.

The fourth set of claims relate to the skills of transfer, and how important it is to teach students to pause and detect the similarities and differences between previous tasks and the new one, before attempting to answer a new problem. Such transfer can be positive, such as when a learner accurately remembers a learning outcome reached in a certain situation and appropriately applies it in a new and similar situation, or negative, such as when a learner applies a strategy used successfully in one situation in a new situation where this strategy is not appropriate. Too many (particularly struggling) students over-rehearse a few learning strategies (e.g., copying and highlighting) and apply them in situations regardless of the demands of new tasks. Certainly, the fundamental skill for positive transfer is stopping before addressing the problem and asking about the differences and similarities of the new to any older task situation. This skill can be taught.

This ability to notice similarities and differences over content is quite different for novices and experts (Berliner, 2001; Chase & Simon) and we do not simply learn from experience but we also learn to experience (Bransford et al., 1999). Preparation for future learning involves opportunities to try our hunches in different contexts, receive feedback, engage in productive failure and learn to revise our knowing based on feedback. The aim is to solve problems more efficiently, and also to 'let go' of previously acquired knowledge in light of more sophisticated understandings - and this can have emotional consequences: 'Failure to change strategies in new situations has been described as the tyranny of success' (Robinson et al., 1998). It is not always productive for students to try the same thing that worked last time. Hence there may need to be an emphasis on knowledge building rather than knowledge-telling (Bereiter & Scardamalia, 1993), and systematic inquiry based on theory-building and disconfirmation rather than simply following processes for how to find some result.

Why some strategies do not work.

The fifth set of claims relate to how the model can be used to resolve some of the unexpected findings about the impact of various teaching methods. In Visible Learning, (Hattie, 2009) it was noted that many programs that seem to lead to developing deeper processing have very low effect sizes (e.g., inquiry based methods, d = .31; problem-based learning, d = .15). For example, there have been 11 meta-analyses relating to problem-based learning based in 509 studies, leading to an average small effect (d = .15). It hardly seems necessary to run another problem-based program (particularly in first-year medicine, where four of the meta-analyses were completed) to know that the effects of problem-based learning on outcomes are small. The reason for this low effect seems to be related to using problem-based methods before attaining sufficient surface knowledge. When problem-based learning is used in later medical years, the effects seem to increase. Albanese and Mitchell (1993) claimed that increased years of exposure to medical education increases the effect of problem-based learning. They argued that lack of experience (and lack of essential surface knowledge) leads the student to make more errors in their knowledge base, add irrelevant material to their explanations and engage in backward reasoning (from the unknown to the givens), whereas experts engaged in forward reasoning (also see Gijbels et al., 2005; Gilhooly, 1990). Walker et al. (2009) also noted that novice problem-based learning students tended to engage in far more backward-driven reasoning, which results in more errors during problem solving and may persist even after the educational intervention is complete. It is likely that problem-based learning works more successfully when students engage in forward reasoning and this depends on having sufficient content knowledge to make connections.

Deep understanding in problem-based learning requires a differentiated knowledge structure (Schwartz & Bransford, 1998), and this may need to be explicitly taught - as there is no assumption that students will see similarities and differences in contexts by themselves. There is a limit to what we can reasonably expect students to discover, and it may require teaching students to make predictions based on features that were told to them and that they may not notice on their own. Deliberate teaching of these surface features can offer a higher level of explanation that would be difficult or time consuming to discover. A higher level explanation is important because it provides a generative framework that can extend one understanding beyond the specific cases that have been analysed and experienced. On the other hand, the problems need not be too overly structured, as then students do not gain experience of searching out conceptual tools or homing in on particular cases of application (Perkins, 2014).

Another example of the different requirements of surface and deep learning is the effect of asking students to explore errors and misconceptions during their learning. Using meta-analysis, Keith and Frese (2008) found that the average effect of using these strategies when the outcome was surface learning was -0.15 and when the outcome was deep learning and far transfer to new problems, it was 0.80.

So: what is learning?

The sixth set of claims relate to the notion of ‘what is learning?’. The argument in this article is that learning is the outcome of the processes of moving from surface to deep to transfer. Only then will students be able to go beyond the information given to ‘figure things out’, which is one of the few untarnishable joys of life (Bruner, 1996). One of the greatest triumphs of learning is what Perkins (2014) calls ‘knowing one’s way around’ a particular topic or ‘playing the whole game’ of history, mathematics, science or whatever. This is a function of knowing much and then using this knowledge in the exploration of relations and to make extensions to other ideas, and being able to know what to do when one does not know what to do (the act of transfer).

Concluding comments.

Like all models, the one proposed in this article invites as many conjectures and directions for further research as it provide a basis for interpreting the evidence from the meta-synthesis. It helps make sense of much of the current literature but it is speculative in that it also makes some untested predictions. There is much solace in Popper's (1968) claim that ‘Bold ideas, unjustified anticipations, and speculative thought, are our only means for interpreting nature: our only organon, our only instrument, for grasping her. And we must hazard them to win our prize. Those among us who are unwilling to expose their ideas to the hazards of refutation do not take part in the scientific game.’

Further research is needed, for example, to better understand the optimal order through the various phases; there may be circumstances where it may be beneficial to learn the deeper notions before developing the surface knowledge. It is highly likely that as one develops many ideas and even relates and extends them, these become ‘ideas’ and the cycle continues (Pegg, 2014). We know much, but we need to know much more, and in particular we need to know how these many learning strategies might be better presented in another competing model. Such testing of a bold model and making predictions from models is, according to Popper, how science progresses.

Further research is needed that asks whether the distinction between the acquisition and the consolidation of learning is a distinctive difference, a melding from one to the other or whether both can occur simultaneously. If there is a difference, then more research on ascertaining the best time to move from acquisition to consolidation would be informative. Similarly, there is no hard rule in the model of a sequence from surface to deep to transfer. In some ways, teaching the strategies of knowing what success looks like upfront implies an exposure to both surface and deep learning. Also, the many arguments (but surprisingly there is a lack of evidence) for the popular notions of flipped classrooms could be supported with more evidence of introducing the success criteria upfront to students. A typical flipped lesson starts with students accessing online video lectures or resources prior to in-class sessions so that students are prepared to participate in more interactive and higher-order activities such as problem solving, discussions and debates (DeWitt, 2014). The most needed research concerns transfer - the variation theory of Marton (2006), the claims by Perkins (2014) and others need more focused attention and the usual (and often unsubstantiated) claims that doing x will assist learning y should come back as a focus of learning sciences.

We are proposing that it is worthwhile to develop the skill, will and thrill of learning, and that there are many powerful strategies for learning. Students can be taught these strategies (declarative knowledge), how to use them (procedural knowledge), under what conditions it may be more or less useful to apply them (conditional knowledge) and how to evaluate them. It may be necessary to teach when best to use these strategies according the nature of the outcomes (surface and deep), according to the timing of learning (first acquiring and then consolidating learning) and to teach the skill of transferring learning to new situations. We need to think in terms of ‘surface to deep’ and not one alone; we need to think in terms of developing dispositions, motivations and achievement, and not one alone. This invites considering multiple outcomes from our schools.

Singapore (Tan & Dimmock, 2014) for example, is now committed to developing an educational system which will produce young people who have the moral courage to stand up for what is right; pursue a healthy lifestyle and have an appreciation of aesthetics; are proud to be Singaporeans; are resilient in the face of difficulty, innovative and enterprising; are purposeful in the pursuit of excellence; are able to collaborate across cultures; and can think critically and communicate persuasively. Academic achievement is but one desirable learning outcome of many.

Another important message is that developing a few learning strategies may not be optimal. The failure to change strategies in new situations has been described as the tyranny of success (Robinson et al., 1997); and the current meta-synthesis suggests that choosing different strategies as one progresses through the learning cycle (from first exposure to embedding, from surface to deep to transfer) demands cognitive flexibility. It may not be the best option for students to use the same strategies that worked last time, as when the context is changed the old strategies may no longer work.

Post-Publication Addendum

Research update.

This data published in this chapter is based as it is on over 228 meta-analyses involving 18,956 studies, 11,006,839 students and 302 effects, and spans published articles from over five decades. Since the publication of the original paper (Hattie & Donoghue, 2016), no published article has challenged these data. The Hattie-Donoghue Model of Learning, proposed as a potential framework into which the various stages and types of learning can be situated, is based on that robust data. The Model of Learning was proposed so that it could be reviewed and analysed and where possible, falsified by subsequent research. To date, despite 151 citations of the article since 2016, there has been no published paper that has challenged the validity of the model.

In contrast, important aspects of the model have been confirmed, by both educational and neuroscience literature. Teig, Scherer and Nilsen (2018) for example have confirmed the non-linearity of the learning trajectory in inquiry-based learning in science; the iterative, non-linear nature of the learning process is a key feature of Model of Learning. Cantor et al (2019) draw parallels between the stages and types of learning outlined in the model and their neurological correlates. In general their paper synthesises learning-related findings from a range of disciplines – including developmental neuroscience, human development and science of learning – and in particular highlights the "distinct brain states" (p. 322) that support different types of learning. The Model of Learning is based on that very distinction: there are separate processes (visible at the psychological / behavioural layer) operating depending on whether the learner is involved in surface, deep or transfer of learning. Finally, some researchers have confirmed the ecological validity of the model (see Fisher & Frey, 2020 for discussion of application of the model to early years learning and Graesser, Lippert & Hampton, 2017 for discussion on the promotion of deep learning).

It is reasonable to conclude therefore that while validation of the model continues to be tested, the data on which the model, and this chapter, is based remains robust and unchallenged. Future research will continue this iterative process of validation.

Success criteria.

The relationship between 'success criteria' and assessments in education, as discussed on page 134 (in the context of the Model of Learning" and again on pages

138-139 (review of the evidence), will now be further clarified. The essential element of this relationship is that a student is more likely to learn more effectively if they understand what success looks like – that is, what must they do to demonstrate that they has learned the required material or skill. As previously discussed in the review section, the evidence is unequivocal in that the better a student understands the criteria of success, the better the student's learning will be. Success criteria -or more precisely, 'a student's understanding of the criteria for success'– is therefore a reliable predictor of a student's learning and achievement, as measured by various learning assessments. Consequently, it is included in the model on page 134, as an important variable that predicts performance on assessments. As it affects all learning outcomes (skill, will, and thrill), during all learning phases (acquisition, consolidation) and learning types (surface, deep and transfer), it has been depicted in the model as a free-floating variable, impacting all others.

Chapter 7.

Conclusions, Corollaries and Contributions

"Wisdom is characterised by the making of finer distinctions, and fewer judgements."

Anonymous.

The primary purpose of this thesis is to establish, conceptually and where possible, empirically, how neuroscience and educational psychology may be meaningfully translated into educational practice. This involved investigating the promises of neuroscience, investigating how realistic or achievable they are, and then comparing the published contributions of neuroscience with the contributions of the educational psychology discipline. The abstracted framework and translation schema have made it possible to empirically evaluate the impact of these two disciplines: first, through a systematic review of neuroscience literature; second through a meta-analysis of educational psychology literature on learning strategies; and third a meta-synthesis of educational psychology literature on learning strategies. This third study also included the proposal of a conceptual model for human learning, based on that literature.

This final chapter provides a summary of the results of these studies, and based on these findings, conclusions about the impact of the two disciplines are drawn. In doing so, the major contributions of this thesis will be highlighted, and finally, potential corollaries of the research will be discussed, and a conceptual model for the Science of Learning proposed.

Summary of Findings

The aim of this thesis is to compare and contrast the impact of educational neuroscience and educational psychology on educational practice, with the view towards the proposal of a conceptual model for the learning sciences. Such a conceptual model could situate and integrate various learning-related disciplines – including but not limited to neuroscience and psychology, and thereby underpin and inform an interdisciplinary science of learning. In order to do this, two artefacts were proposed, described and implemented in this thesis.

Translation.

First, a layered abstracted framework was proposed (Chapter 2 and peer-reviewed published as Donoghue & Horvath, 2016), in which all disciplines that in any way relate to human learning could be situated in a logical and practical schema, categorised according to levels of complexity and analysis (Anderson, 2002). This framework situated psychology in the Individual layer (consisting of persons, made up of cells, organs and interactions between them that result in behaviour, cognition and physiology), and neuroscience in the Organellular or Cerebral layer (consisting of discrete, functional organs – such as the brain – that in turn are made up of individual cells), and the Cellular layer (consisting of individual cells). Education in contrast was situated in the Sociocultural layer (consisting of several individuals, and the complex interactions between them).

Second, a translation schema was proposed (Chapter 3 and peer-reviewed published as Horvath & Donoghue, 2016), in which four different types of translation between the layers in the Abstracted Framework were described: functional, conceptual, diagnostic and prescriptive.

The impacts of educational neuroscience.

These two artefacts underpinned the hypothesis of the study that prescriptive translation between discontiguous layers in the framework was not possible. To test this hypothesis, Chapter 4 reported on a systematic review of the educational neuroscience literature, and found that despite many promises and optimistic claims, there was no single published study that prescriptively translated into educational practice – that is, there was no finding from neuroscience that directly informed how teachers should conduct their professional practice, or what students should do to enhance their own learning. Of the 548 articles reviewed, none were classified as being prescriptively translatable into Layer V of the framework, despite the fact that many purported or promised to do so. This is, of course, not to say that such an impact is impossible in the future; but it is to say that, to date, educational neuroscience has failed to deliver on its promise of profoundly impacting educational practice.

The impacts of psychology.

These findings have highlighted an important distinction between psychology, neuroscience and education: each conceive of learning very differently. While educational psychology in this thesis focuses on the academic aspects of human learning, neuroscience conceives learning as a far broader biological adaptation. As a discipline, it is a subset of evolutionary biology, and through that lens, human learning is a biological adaptation that evolved primarily through natural, sexual and cultural selection, and is applicable in a broad array of ever-changing external and internal environments. Through a neuroscientific lens, learning is essentially a complex neurological phenomenon that occurs predominantly, but not exclusively, in the brain.

In contrast, education is an even more complex sociocultural phenomenon, that is both temporally and culturally relative, and incorporates all subordinate disciplines including the psychological, biological, physical and chemical sciences. Through an educational lens, learning involves the development – intended and unintended – of a learner's behaviour, skills, knowledge and cognition. This development may result from the learner's own behaviours and internal thought processes, and may also result from external sources as the transfer of knowledge and skill from another individual, or from the external environment. Often these learning experiences are deliberately invoked in order to achieve explicit desirable learning outcomes, other times they are invoked incidentally, and at all times may result in undesirable learning outcomes. These disparate conceptualisations of human learning present a challenge to the integration of these learning-related disciplines, and demonstrate the importance of valid translation into education.

To compare the impact of neuroscience with the impact of educational psychology, the second study involved a meta-analysis of the educational psychology literature relating to learning strategies. This study confirmed the long and influential history of well-replicated research that directly informed educational practice, that is to say, was translatable from educational psychology (Layer IV) into the classroom (Layer V). It also revealed that an overwhelming proportion of this literature relied on a specific, arguably narrow, conceptualisation of human learning: the ability of North American adults of normal ability to immediately recall surface level, near-transferred facts in academic domains the short-term recall of surface level, near-transferred factual information from academic disciplines. Dunlosky et al.'s qualitative ranking of the top 10 strategies was supported empirically in this study: all strategies had effect sizes over .5 (well above Hattie's hinge point of .4). The best strategies, those that exceeded .8, were all related to practice, a form of repetition that is in accordance with Hebbian learning (Hebb, 1949).

The third study, a meta-synthesis of the educational psychology literature, sought to build on the findings of the second study by meta-synthesising research on learning strategies, and to explore the viability of an empirically-based model of human learning. It revealed a vast and long-standing history of psychological evidence on learning strategies, albeit still constrained by evidence based on studies that privileged, inter alia, surface learning and academic achievement. The sheer volume of the data and proximal hypotheses analysed in this study indicated the need for a conceptual, even theoretical, model into which these proximal theories could be cohered into a more distal educational theory. In doing so, the model adopted an expanded conceptualisation of human learning involving measurable inputs, an interventional environment, and measurable outputs. Further, these inputs and outputs were not constrained to simply academic achievement, but expanded to include the *skill, will and thrill* of learning, in recognition of the a range of outcomes that are achievable – both desirable and undesirable - when humans learn.

Conclusions

Neuroscience translates to education conceptually but not prescriptively.

It is the first conclusion of this thesis that neuroscience is yet to provide any significant impact on educational practice, despite many promises and predictions to the contrary. In the so-called 'decade of the brain', neuroscientists, psychologists and educators have strived to make the case that an understanding of the brain will be fundamentally important to pedagogy, and that teachers who attempt to teach without such an understanding are akin to 'glove makers with no knowledge of the hand' (de Sousa, 2010). This has spawned a new discipline – educational neuroscience – with hundreds of peer-reviewed articles, books, programs, even dedicated academic journals. The field is now an accepted, albeit fledgling, discipline, with a life of its own.

But as Breuer (1997) presciently observed, and others have since confirmed (Bowers, 2016; Mayer 2017), the challenge facing this discipline is to draw some meaningful link between the two fields. Breuer's most recent work (2016) shows that 20 years later, the field is replete with promises, speculations and non-sequiturs, and has had limited impact on educational practice. This has been supported on theoretical and conceptual grounds by Bowers (2016), and now on empirical grounds by the systematic analysis of neuroeducational literature presented in Chapter 4.

Many proponents remain optimistic for its future (see Howard-Jones & Holmes, 2016; Howard-Jones et al., 2016), however the available evidence is clear that neuroscience is yet to deliver much of its promise. This thesis supports the argument that neuroscience can be and has been translated into education conceptually, diagnostically and functionally, but not prescriptively. The bridge has indeed, to date at least, proved too far.

Educational psychology informs educational practice.

In Chapter 5, 399 studies that examined 10 common learning strategies were analysed. The studies were analysed without reference to or reliance upon any neuroscientific knowledge, and were measured for effect sizes on learning outcomes. All 399 studies were conducted in the Individual or Sociocultural layers of the abstracted framework, and all purported to be prescriptive on how learning and/or teaching ought to be conducted in the sociocultural layer. The literature was analysed using a meta-analysis to provide a benchmark against which the quality and effectiveness of the translation of neuroscience can be compared.

The second conclusion of this thesis is that educational psychology has a long and substantial history of research that directly and prescriptively impacts educational practice. By conducting research in the Individual layer of the Abstracted Framework, educational psychology has generated a myriad of hypotheses and concepts that have been empirically tested in real-life classroom applications. In so doing, its impact on education is far broader, more substantive and more long-standing than that of neuroscience, and provides both educators and learners with real-world interventions that enhance learning and that can be readily deployed in educational practice. Mayer (2017) has recently reached a similar conclusion - that educational psychology is the ideal bridge between education and neuroscience, probably more so than cognitive science as proposed by Bruer (1997).

Constraining this finding of a substantial impact, the analysis in this thesis also demonstrated that many of the studies investigating the direct impact of learning strategies were focused on only a narrow conceptualisation of human learning. That is to say, learning that is measured by short- (rather than medium- or long-) term recall of surface (rather than deep) level, factual, academic knowledge (rather than conceptual, procedural or cognitive skills) that is not transferrable. Neuroscience, if nothing else, makes it clear that human learning is far broader than this – a finding that indicates a need for broader-based models of learning and teaching that accommodate this breadth of human learning.

Translation is bi-directional.

The systematic review identified research that translated from education *down* to neuroscience and psychology, but no research that translated prescriptively *up* into education. The Translation Schema outlined in Chapter 3 was based implicitly on the assumption that translation was unidirectional – from less complex layers *up* into the education layer. This is known as *bottom-up* translation, where a finding from neuroscience or psychology (Layer III or IV) is applied to the sociocultural layer (Layer V). The findings in systematic review did not support this assumption, revealing that a significant number of studies that demonstrated *top-down* translation education into psychology and/or neuroscience.

Translation is bidirectional – educators can inform, as well as be informed by, other disciplines. Despite published suggestions that such bidirectional translation is viable (Bowers 2016; Mason, 2009), top-down translation was not included in the Translation Schema, and given these results, it should have been. Since this analysis was conducted, Mayer (2017) has reached a similar conclusion: . “. . .the history of the relation between psychology and education shows that a one-way approach is not likely to be effective because of difficulty in directly applying psychological research (including neuroscience-informed psychological research) to education.” (p.839)

Conceptual models and frameworks benefit both neuroscience and the science of learning.

It is the third conclusion of this thesis that conceptual and theoretical models have proved to be both necessary and of significant benefit in this research. This benefit is considered likely to continue and to extend to any discipline that purports to impact educational practice, and it is this conclusion that underpins the recommendations for future directions in the next and final section.

The analyses performed in this thesis were underpinned by two such models - Layered Abstracted Framework and the Translation Schema. These artefacts were of tangible benefit in organising vast amounts of empirical data, theories and untested predictions that are found in the various bodies of literature. Given the recent explosion in the popularity of neuroscience and its application to education, it is a reasonable expectation that the amount of evidence collected in the field will continue to burgeon – indicating a need for a conceptual frameworks into which that growing and often unwieldy corpus of evidence can be organised.

Further, these artefacts underpinned the proposal of a conceptual model of learning (the Hattie-Donoghue model, Chapter 6) that was based on the empirical data found in the meta-analysis and meta-synthesis. It acknowledges that all learning occurs in an environmental context that cannot be ignored – learning unavoidably impacts, and is impacted by, that context. Further, it identifies the varying impacts of particular learning strategies depending on the learner's stage of development, the type of material to be learned, and the type of learning that is targeted (acquisition, consolidating deep, transferrable,). Finally, it recognises that the outcomes of learning, desirable and otherwise, are not restricted to academic achievement but also include emotional (the 'thrill'), psychological (the 'will'), and physical and cognitive ('the skill') outcomes. It is deliberately based on evidence from educational psychology literature – a body of evidence dominated by studies of academic achievement. This proposed model incorporates a broader conceptualisation of learning (the skill, will and thrill), recognised different phases (acquisition and consolidation), and different depths of learning (skill, will, and transfer).

Conceptual models and frameworks have proved of practical and real benefit in this research. Models such as those proposed in this thesis help conceptualise and organise vast and disparate bodies of data, and allow for the integration of that data into interdisciplinary fields such as learning-related sciences.

Corollaries

The empirical findings of this thesis present an important corollary for future research. Given their respective strengths and limitations, in what ways can these learning-related disciplines best inform educational practice in the future? This final section will discuss one proposed way in which this may occur – and that is the development of a conceptual model for the Science of Learning – a superset of learning-related scientific disciplines - within which future research can be situated.

Bidirectional translation.

The existence of this top-down translation confirms Bowers' (2016) and Mayer's (2017) conclusions that translation between the disciplines is most effective when it is bidirectional. Neuroscience, because it focuses largely on identifying the neural correlates of human learning, relies heavily on what education can confirm when and how learning is actually occurring. Neuroscience therefore needs education, and in Bowers' terms, does so far more than education needs neuroscience. This perspective has important corollaries for educators, not least of which relate to the professionalism and status of education as a profession demonstrating capable of top-down translation. This perhaps reflects the anecdotal notion expressed by Hattie (personal communication, September, 2018) that "as a profession, educators largely deny their own expertise", a phenomenon perhaps underpinning the tendency of educators to defer to experts in non-educational disciplines such as psychology and more recently neuroscience. This tendency may in turn explain why educators often follow educational fads promoted by commercial interests. Further, the foundational assumption, explicated routinely in the mission statements of learning science centres, is that neuroscience and cognitive psychology will inform educational practice. Moreover, both of these fields may in fact serve as the entry point into evidence-based, scientifically-grounded, educational practice.

Australia's flagship Science of Learning Research Centre is a case in point – the primary purpose of this Australian Research Council funded centre was to investigate ways that science – especially neuroscience – can inform and improve educational outcomes for students. The implicit assumption in its remit was that educators need to be informed by neuroscience and/or psychology, whereas the systematic review in this thesis suggests that educators have more expertise in human learning – as it occurs in the complex sociocultural context that is the modern classroom – than any other expert, neuroscientists and psychologists included. Perhaps this assumption arises from the fact that education is traditionally not considered an evidence-based profession, and that educators tend to deny their own expertise.

In contrast, though, perhaps education's recent interest in and adoption of neuroscience is a means by which an evidence-based approach can be adopted in education. If so, such a foray is to be encouraged. By empowering teachers to learn about neuroscience and psychology and incorporate the scientific method and its rigour into their practice, education may thereby become a more evidence-based profession. Educational neuroscience, in this way, may have a Trojan horse effect: educators are initially drawn in by the 'seductive allure' of neuroscience – as evidenced by the overwhelming popularity neuroscience currently enjoys - and in so doing are exposed to the fundamentals of scientific evidence. By becoming literate in the scientific approach to learning and teaching, educators may become more evidence-based practitioners. This is being seen in the uptake of Visible Learning (Hattie, 2009) and other evidence-based research, but much more progress in the critical analysis of practices, assumptions and evidence is necessary. By emboldening educators, armed with their newly found scientific and evidence-based rigour and the ability to translate in to and from their profession, they may lead other disciplines to find new ways of conceptualising, measuring and enhancing human learning that can in turn be translated back up into education, thereby enhancing educational practice.

Towards a conceptual model.

As stated in the Conclusions subsection above, the use of the Abstracted Framework and Translation Schema were instrumental in making sense of a vast and disparate body of learning-related evidence. They contributed to the development of the model of learning (Chapter 6) and as such proved to be of significant benefit, despite being – by design – constrained to evidence on mainly academic achievement. A corollary of this finding is that the development of other models, more comprehensive and capable of incorporating more empirical data, may in the future contribute even more benefit.

Further, this thesis has demonstrated that multiple disciplines can inform educational practice, albeit not always prescriptively, assuming that translation between those disciplines is valid. Similarly, educational practice can inform and be translated into, those other disciplines. It is proposed that therefore that education will be beneficially impacted when scientific research – from multiple disciplines - is integrated and then validly translated into and from educational practice. To this end, the development of a comprehensive conceptual model that subsumes and integrates the various learning-related disciplines within this one field, is warranted. Such a model could provide the foundation for the interdisciplinary field of the Science of Learning, so in the final section of this thesis, one such conceptual model is proposed.

There are several important features of this model, the first of which is that the model is theory-driven, and underpinned by ultimate or distal theories and conceptualisations such as those presented by other disciplines including neuroscience. Ideally, such a model would integrate these disciplines such that the Science of Learning can be grounded on a distal or ultimate theoretical foundation, such as evolutionary biology (or at least the biological sciences of which neuroscience is a part).

Geary’s attempt to align education with evolutionary theory is a standout example of this, and future research is likely to benefit from the development the field he and others pioneered - evolutionary educational psychology. This would distinguish it from many current educational research and practices that are either atheoretical, or based on proximate theories only.

The second essential feature of such a model is the capability to subsume all learning-related disciplines, most notably neuroscience and cognitive psychology, but also disparate fields such as sociology, anthropology, design for learning (see Goodyear & Dimitriadis, 2016 for an overview) computer technology and learning analytics (see Donoghue, Horvath & Lodge, 2019) and related fields, as well as direct in situ educational research (see by Hattie, 2007; Chan, Ochoa & Clarke, 2020).

The third essential feature, arising from the second, is that the model ought to incorporate more valid and comprehensive conceptualisations of learning than the model proposed in Chapter 6. As previously discussed in detail, the conceptualisations of human learning vary significantly between the layers in the Abstracted Framework. Different disciplines see human learning in very different ways. Educational psychology views learning through an individual, largely behavioural lens, while neuroscience conceives of learning as a biological adaptation that evolved to enhance biological fitness, and as such is viewed as a biological, even chemical, phenomenon. Education, in contrast, is able to conceive of learning as a much broader phenomenon. Learning impacts, and is impacted by, all dimensions of human existence including phenomena in the sociocultural, individual, psychological, emotional, cognitive and chemical and physical domains. Primarily, however, education is geared towards pedagogy - the deliberate facilitation of human learning with the view to achieving particular learning outcomes, both implicit and explicit.

Despite the foundational differences between these conceptualisations, often the same language is used to describe them. Consider, for example, the use of the word ‘learning’ – this same word is used to denote such different phenomena as what computer algorithms do (in, for example, machine learning), what humans do in classrooms (formal learning) or even what happens to *in vitro* neuronal networks (learning in neuron cultures). Any effective conceptual model would both situate and distinguish between these disparate conceptualisations and thereby overcome this linguistic confusion.

Fourth, valid and meaningful translation between these fields would be of critical importance. This necessitates the incorporation of top-down translation – a type of translation that was omitted in the original model. As the data analysis in this thesis has indicated, top-down translation is common, valid and now supported by subsequent research. This feature would allow for the reconciliation of these disciplines of the field, and enable meaningful, valid and bi-directional translations between them, such that educational practice may be informed by and benefit from the scientific findings from all subordinate, learning-related discipline, not just those that are currently in favour.

There are many disciplines that can impact human learning, and by extension, education – hence many potential contributors to the science of learning. A worthy corollary of this thesis is that valid translation is key to any interdisciplinary field – if only to avoid the perpetuation of neuromyths, non sequiturs and other logical fallacies, whilst deriving the best benefits for multiple disciplines.

Finally, an effective model would enable and accommodate the clear explication of those learning outcomes that are most worthy of pursuit. It would make explication of those desirable learning outcomes important, hence even impinge on the notion of the philosophy and purpose of education, a subject outside of the scope of this thesis but critically important in any robust scientific enquiry, and hence essential in any theoretical model.

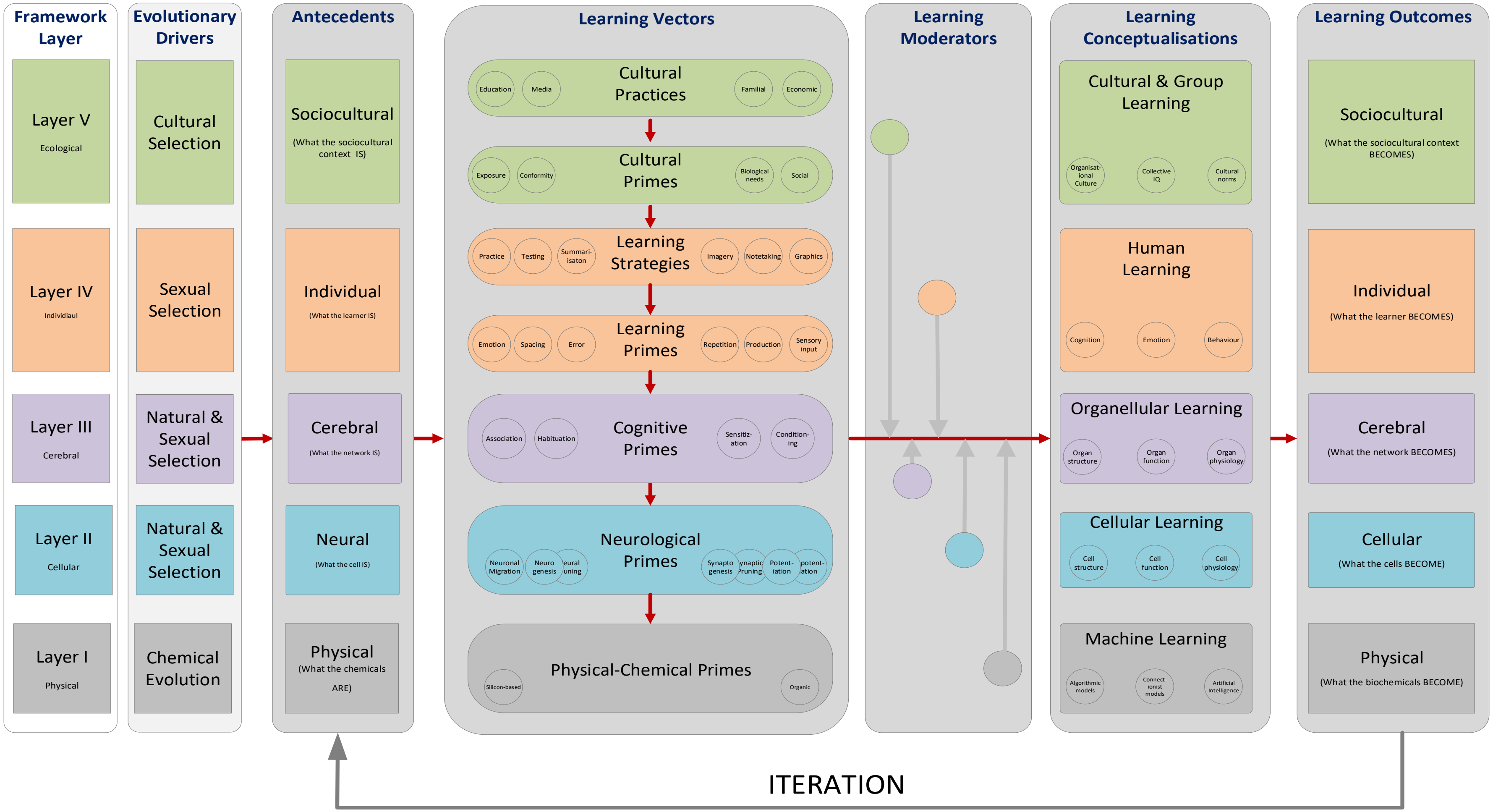
In Figure 7-1 these essential features have been incorporated into a proposed structure for such a comprehensive conceptual model for human learning. It is proposed that educational practice may benefit from the application of such a model where each layer and column is populated with specific hypotheses and research questions, that can then in turn be tested empirically. When validly translated, the results from such theory-driven research is more likely to be theoretically and empirically sound, and less likely to generate neuromyths and other misconceptions.

In short, the model consists of a vertical axis that comprises the layers from the Abstracted Framework, and a horizontal axis that comprises an extension of the elements in the Hattie-Donoghue model proposed in Chapter 6. The base layer is the Physical layer – where learning is instantiated in non-living, non-cellular phenomena such as silicon-based computer hardware, electronic-based computer software, and 'intelligent' molecules such as proteins that can store information. All layers above this relate to learning in cellular organisms.

Moving from left to right, the first of these elements is the *evolutionary drivers* column – reflecting the biological bases of learning. The next element, the *antecedents* reflect a similar element in the Hattie-Donoghue model – the abilities, dispositions and knowledge that a learner brings to the learning experience – their starting point. Next is the *learning vectors* column, in which is situated all interventions that can act as levers on learning. The impact of these interventions will be moderated and mediated by other factors, and these are included in the fourth column entitled *moderators*. The final two columns denote the results or outcomes of learning – first, the *conceptualisations* column provides for valid definitions and delineations of learning at each layer, and second the *learning outcomes* column that situates the final results of the learning trajectory, described in terms applicable to each of the layers.

In this model, the learning process is infinitely iterative – whereby the final outcomes in the rightmost column cycle back to become the starting point, or antecedents, of the next iterations. This rightmost column is worthy of special note – it is here that desirable learning outcomes can be explicated at each of the layers in the Abstracted Framework. While the question of *how* these outcomes can be best achieved is an *empirical science* question, ultimately the question of which outcomes are desirable and which are not is a *values* (or philosophical) question, not an empirical one. It is proposed that the explication of these desirable outcomes is an essential starting point for educational pursuit (see Glaxton, 2013, Postman, 1995; Postman & Weingartner, 1969) – educational practice needs to 'start with the end in mind' (Covey, 1989). This leads ineluctably to questions about the philosophy of education and it purpose – outside this scope of this thesis but worthy of future research and theoretical development.

Figure 7-1. *The pedagogical primes model for the Science of Learning.*



Summary of Contributions

Abstracted conceptual framework.

Based on similar models in other disciplines, the Layered Abstracted Framework was proposed in Chapter 2 and peer-reviewed published (Horvath & Donoghue, 2016). It underpinned the analysis in Chapter 4 and proved to be practicable and valid in distinguishing between the disciplines – it was sufficient to logically categorise both the source and applied data in all 363 neuroscience articles in this systematic review.

Translation schema.

In Chapter 5, a translation schema was proposed (peer-reviewed published in Donoghue & Horvath, 2016). This schema described four types of translation between the layers described in the Abstracted Framework, and was also used in the analysis in Chapter 4, where it proved to be practicable and valid. It has enabled a large corpus of research to be systematically and validly categorised, and has thereby contributed to a better understanding of educational research – as it requires researchers and educators to be more specific – and often even circumspect – in the conclusions they draw about their research. Application of the schema, in conjunction with the framework, exposes the common and illogical practice of collecting evidence in one layer then making non sequitur conclusions in another.

Systematic review.

The application of the two previous artefacts – the translation schema and abstracted framework – allowed for the systematic review of the educational neuroscience literature, and this provided the first empirical analysis of the true impact of this field on educational practice. It showed that despite many promises, claims and expectations of ‘possible’ future application, educational neuroscience has not yet published any research that directly prescribes how educators ought to teach. This study’s results supports the primary hypothesis of this thesis.

The meta-analysis.

Another aim of this thesis was to compare and contrast the impact of educational neuroscience with that of educational psychology, and to this end a meta-analysis on learning strategies was conducted. This meta-analysis of 399 studies (reported in Chapter 5 and currently under peer-review as Donoghue & Hattie, 2016), revealed that educational psychology as a discipline enjoys a long and substantial history of robust, sound and well-replicated research – research that has direct applicability in educational contexts. Compared to educational neuroscience, educational psychology (or more recently, so-called cognitive neuroscience) has had a dramatic impact on education – perhaps confirming Bruer’s (1997) prescient prediction that cognitive psychology would be the mediating span in the ‘bridge too far’ between neuroscience and education.

The meta-synthesis and model of learning.

Building on the meta-analysis, Chapter 6 contributed a meta-synthesis of a broader evidence-base, again on learning strategies. This study confirmed the findings in the meta-analysis – that there is a long and robust history of educational psychology literature that has had direct and significant impact on educational practice. It also confirmed that this evidence was largely based on short-term recall of near-transferred surface level factual knowledge in academic disciplines. Despite these constraints, this synthesis identified evidence that supported a conceptual model of learning that is broader than this – incorporating non-academic aspects of human learning, namely the skill, will and thrill of learning.

Towards a conceptual model for the Science of Learning.

Building on these findings and the model for learning proposed in Chapter 6, this thesis has also proposed elements of a comprehensive conceptual model for the Science of Learning. Such a model can situate and integrate the disparate learning-related sciences, including but not limited to psychology and neuroscience, and may be used to guide future research. Further, it allows for multiple and clearly distinguished conceptualisations of human learning, and the explication of desirable learning outcomes - features that are likely to aid future educational practice and research.

Concluding Remarks

In the medical sciences, a field that has clear and immediate life-and-death consequences, a rigorous scientific approach is the norm. The mandate of evidence-based practices has saved and extended many lives. There exist strong legal and bureaucratic systems in place that ensure that patients only receive treatments that are validated by reliable and robust scientific enquiry, and will work towards explicated desirable outcomes and minimise undesirable side effects.

The effects of human learning – and therefore education - can also be life-and-death. Statistics abound on the tragic consequences that befall people who have not learned what they need in order to function optimally – including accidents, ill-health, poverty, misadventure, relationship dysfunction, even self-harm, suicidality and crimes that arise from an inability to regulate one’s behaviour and emotions.

Education changes brains, it changes people and their behaviour, and it changes the world around them. Education is a powerful causal factor in human learning, and its impacts are therefore equally of life-and-death importance – except that those impacts are not necessarily immediate or proximate. Given this importance, the challenge for educators is to become evidence-based and scientifically rigorous, and to implement practices that are based on robust scientific findings.

Neuroscience is by definition the science of neurons, and psychology the science of human cognition and behaviour. At their core, neither of these disciplines are dedicated sciences of human learning - they are discrete disciplines that intersect and overlap with the study of learning. Learning is a multi-faceted phenomenon or construct, with physical, neurological, psychological and sociocultural elements. This thesis has demonstrated the limitations of the individual disciplines of neuroscience and psychology, and the inherent difficulties in translating between them and education. It has lent support to the notion that a comprehensive interdisciplinary field of Science of Learning will be effective in establishing the evidence-based foundation for education, and it has proposed several necessary elements of a comprehensive conceptual model for that interdisciplinary science.

The importance of neuroscience and psychology in understanding human learning cannot be overlooked. Notwithstanding, education exists in a complex sociocultural context that subsumes neurology, psychology, even physics and chemistry. For education to benefit from science, both educational neuroscience and educational psychology (along with other learning-related disciplines) need to be subsumed by the interdisciplinary field of the Science of Learning. Such a field would be an *ecological* science, and would therefore necessarily involve *ecological* methodologies and epistemologies, and rely on an ecologically-sound theoretical model.

This thesis has provided support for the notion that the impact of neuroscience has not matched its hype, and that there are certain constraints on the impact of the educational psychology research reviewed. This need not however be seen as a totally negative finding – psychology is not dead, despite Gazzaniga's dim view, and neuroscience is not completely irrelevant to education, despite Bower's dim view. The findings in this thesis point to the potential benefits of a comprehensive, evidence-based and validly-translated model for the Science of Learning that subsumes many learning-related disciplines. This thesis aims to contribute, in some small part, towards that conceptual model for the Science of Learning, an important interdisciplinary field, comprised of but not restricted to psychology and neuroscience. The Science of Learning, with its broad range of subsumed disciplines, scientific rigour, sound and explicated theoretical foundations, and a broad-based conceptual framework such as the one proposed, is well placed to inform educational practice such that it can most efficiently deliver those learning outcomes that society has explicated as most desirable.

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Key to Prefixes

# denotes references included in the systematic review in Chapter 4

* denotes references included in the meta-analysis in Chapter 5

^ denotes references included in the meta-synthesis in Chapter 6

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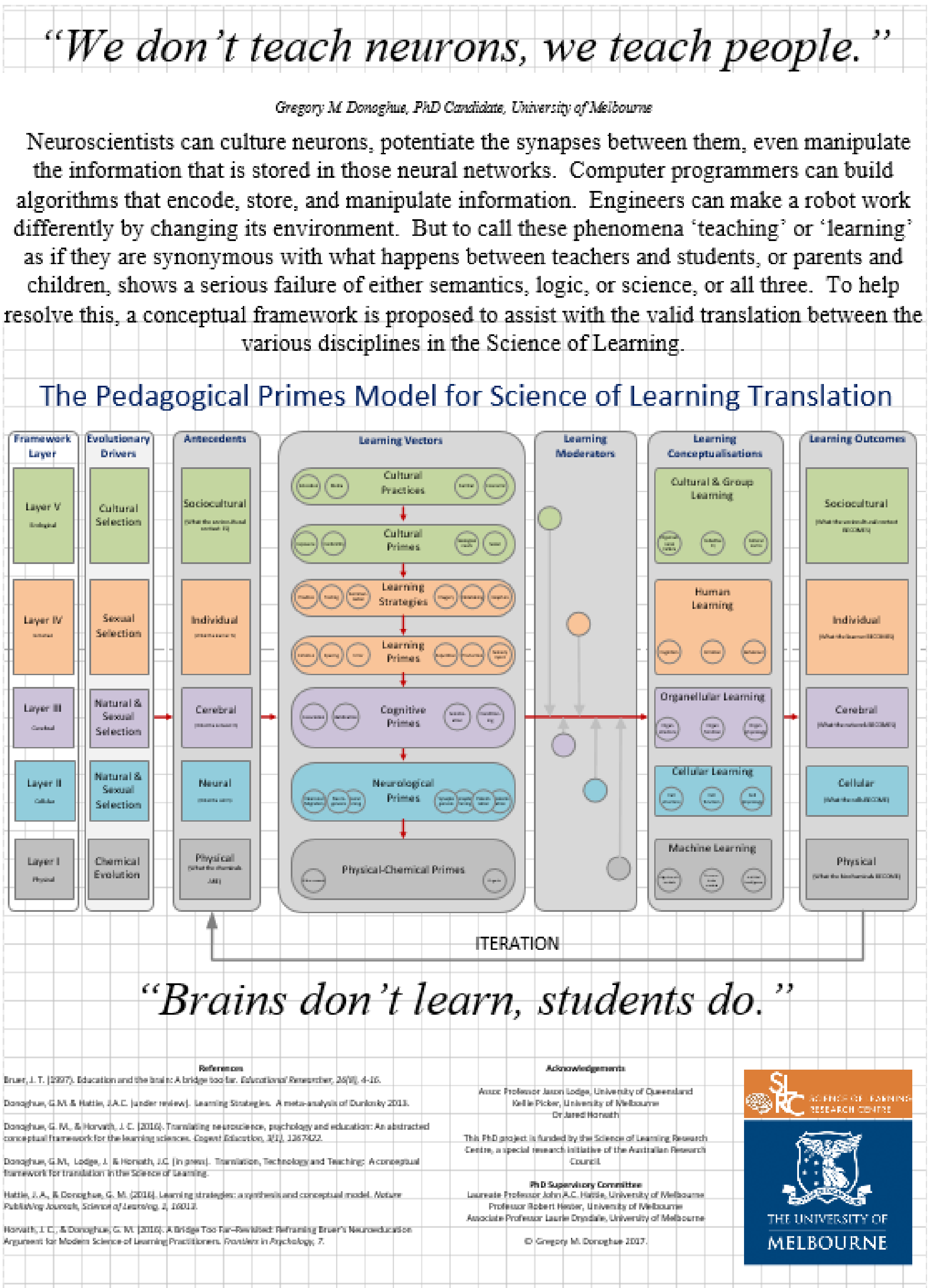
Appendices

Appendix 1: Poster Presented to 2017 International Science of Learning Conference, Brisbane, 18th- 20th September, 2017.



Appendix 2: Chapter 5 Donoghue & Hattie Meta-Analysis Summary Table.

Authors	Year	Strategy	Impact Factor	N.	Grade	Country	Design	Transfer	Domain	Depth	Delay	Ability	ES	No effects
Agarwal & Roediger	2011	Practice testing	2.463	72	Univ	USA	Control-Exp	Far	English	Surface	2 days	Normal	0.82	4
Agarwal, Karpicke, Kang, Roediger & McDermott	2008	Practice Testing	1.414	36	Univ	USA	Control-Exp	Near	English	Surface	7 days	Normal	0.94	1
Ainsworth & Burcham	2007	Self-explanation	4.071	24	Univ	UK	Control-Exp	Near	Science	Surface	< 1 day	Normal	1.16	14
Aleven & Koedinger	2002	Self-explanation	2.496	53	Sec	USA	Control-Exp	Near	Mathematics	Surface	< 1 day	Normal	1.43	1
Amer	1994	Highlighting/ Underlining	1.545	99	Univ	Oman	Pre-post	Near	Gn knowledge	Deep	< 1 day	Normal	0.39	2
Amlund, Kardash & Kulhavy	1986	Re-reading	1.65	120	Univ	USA	Longitudinal	Near	English	Surface	< 1 day	Normal	0.93	24
Anderson & Thiede	2008	Summarization	3.016	174	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.11	4
Anderson & Hidde	1971	Imagery for Text	2.909	24	Univ	USA	Exp-control	Near	English	Surface	< 1 day	Normal	2.21	2
Anderson & Kulhavy	1972	Imagery for Text	2.909	62	Sec	USA	Exp-control	Near	English	Surface	< 1 day	Normal	0.34	1
Annis	1985	Summarization	0.72	33	Univ	USA	Control-Exp	Near	English	Surface	7 days	High	-0.10	24
Appleton-Knapp, Bjork & Wickens	2005	Distributed practice	2.783	96	Univ	USA	within-subj	Near	Academic	Surface	< 1 day	Normal	0.47	4
Armbruster, Anderson & Ostertag	1987	Summarization	1.65	82	Prim	USA	Control-Exp	Near	Humanities	Surface	11 days	Normal	0.59	1
Atkinson & Raugh	1975	Keyword Mnemonic	0	52	Univ	USA	Exp-control	Near	Languages	Surface	4 days	Normal	1.73	1
Balch	1998	Practice testing	0.975	45	Univ	USA	Control-Exp	Near	Science	Surface	7 days	Normal	0.38	3
Balch	2006	Distributed practice	0.975	145	Univ	USA		Near	English	Surface	< 1 day	Normal	0.88	3
Balota,Duchek, Sergent-Marshal, & Roediger	2006	Distributed Practice	2.913	29	Univ	USA	Exp-control	Near	English	Surface	< 1 day	Normal	1.02	12

Bangert-Drowns, Kulik, & Kulik	1929	Practice testing	1.282		Univ	USA		Near	Humanities	Surface	1 day	Normal	0.23	35
Barcroft	2007	Practice testing	1.433	24	Univ	USA		Near	English	Surface	< 1 day	Normal	0.10	3
Barnett, & Seefeldt	1989	Re-reading	1.101	72	Univ	USA	Exp-control	Near	Humanities	Surface	< 1 day	Normal	0.58	8
Bean, & Steenwyk	1984	Summarization	1.101	41	Prim	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.98	4
Berry	1983	Self-explanation	2.591	60	Univ	UK	Control-Exp	Near	English	Surface	< 1 day	Normal	0.04	1
Bishara & Jacoby	2007	Practice testing	2.986	36	Univ	USA	Time-series	Near	English	Surface	< 1 day	Normal	1.25	1
Bloom & Shuell	1981	Distributed practice	1.282	56	Sec	Canada	Control-Exp	Near	Languages	Surface	< 1 day	Normal	1.00	1
Bretzing & Kulhavy	1979	Summarization	3.159	36	Sec	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.37	16
Brooks, Dansereau, Holley, & Spurlin	1983	Summarization	3.159	35	Univ	USA	Control-Exp	Near	Academic	Surface	< 1 day	Normal	0.48	16
Brozo, Stahl,& Gordon	1985	Summarization	0	49	Univ	USA		Far	English	Surface	5 weeks	Normal	-0.68	4
Budé, Imbos, van de Wiel & Berger	2011	Distributed practice	1.124	64	Univ	Neth	Time-series	Near	English	Deep	6 months	Normal	0.79	2
Butler	2011	Practice testing	3.098	48	Univ	USA		Near	English	Surface	7 days	Normal	1.15	13
Butler & Roediger	2007	Practice testing	1.21	27	Univ	USA		Near	Humanities	Surface	28 days	Normal	1.22	1
Butler, Karpicke, & Roediger,	2008	Practice testing	3.098	30	Univ	USA		Near	Gn knowledge	Surface	< 1 day	Normal	1.03	2
Callender & McDaniel	2009	Re-reading	3.159	66	Univ	USA	Longitudinal	Near	English	Surface	< 1 day	Normal	0.15	23
Callender & McDaniel	2007	Elaborative Interrogation	2.909	56	Univ	USA		Near	Science	Surface	< 1 day	Normal	0.06	14
Carlson & Shin.	1996	Interleaved practice	3.098	45	Univ	USA	exp-control	Near	Mathematic s	Surface	< 1 day	Normal	1.74	8
Carlson & Yaure	1990	Interleaved Practice	3.098	66	Univ	USA	Exp-Control	Near	Logic	Surface	< 1 day	Normal	0.56	2
Carlson & Yaure	1990	Interleaved Practice	3.098	57	Univ	USA	Exp-Control	Far	Logic	Surface	< 1 day	Normal	2.76	2
Carpenter & DeLosh	2005	Practice testing	1.414	62	Univ	USA	Control-Exp	Near	Academic	Surface	< 1 day	Normal	0.95	2

Carpenter, Pashler & Cepeda	2009	Practice testing	1.414	62	Sec	USA	Control-Exp	Near	Humanities	Surface	7 days	Normal	0.84	2
Carpenter.	2009	Practice testing	3.098	59	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.69	2
Carpenter	2009	Practice testing	3.098	212	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.84	7
Carpenter & Pashler	2011	Practice testing	2.986	52	Univ	USA	Control-Exp	Near	Humanities	Surface	< 1 day	Normal	0.82	4
Carpenter Pashler & Vul	2011	Practice testing	2.986	176	Adult	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	1.38	2
Carpenter, Pashler, Wixted & Vul	2008	Practice testing	2.021	55	Adult	USA		Near	Gn knowledge	Surface	< 1 day	Normal	0.28	21
Carroll, Campbell-Ratcliffe, Murnane & Perfect	2008	Practice testing	1.21	64	Univ	Aust		Near	Science	Surface	1 day	Normal	0.24	7
Cashen & Leicht	1970	Highlighting/ Underlining	6.261	40	Univ	USA	Control-Exp	Near	Gn knowledge	Deep	< 1 day	Normal	0.56	1
Cepeda, Coburn, Rohrer, Wexted, MOzer, Pashler	2009	Distributed practice	1.95	233	Univ	USA	Time-series	Near	English	Surface	1-168 days	Normal	0.54	5
Cepeda, Pashler, Vul, Wixted & Rohrer	2006	Distributed practice	14.392	18	Univ			Near	English	Surface	7 days	Normal	0.63	7
Cepeda, Vul, Rohrer, Wixted & Pashler	2008	Distributed practice	6.501	125	Univ			Near	English	Surface	7 days	Normal	1.31	8
Cermak, Verfaellie, Lanzoni, Mather & Chase	1996	Distributed practice	3.425	26	Univ	USA	within-subj	Near	English	Surface	< 1 day	Normal	1.26	3
Chan, Cole & Morris	1990	Imagery for Text	1.44	26	Prim	Aust	Control-Exp	Near	English	Surface	< 1 day	Normal	0.11	12
Chan	2010	Practice testing	2.463	84	Univ	USA		Near	Humanities	Surface	7 days	Normal	1.78	1
Chan	2009	Practice testing	5.118	96	Univ	USA		Near	Humanities	Surface	< 1 day	Normal	1.66	2
Chan, McDermott, & Roediger	2006	Practice testing	5.495	84	Univ	USA		Near	Science	Surface	1 day	Normal	1.10	9
Chi & de Leeuw	1994	Self-explanation	2.496	14	Sec	USA	Control-Exp	Near	Science	Surface	< 1 day	Normal	4.61	1
Coppens, Verkoeijen & Rikers	2011	Practice testing	1.21	50	Univ	Neth		Near	Academic	Surface	< 1 day	Normal	0.98	3
Cranney, Ahn, McKinnon, R., Morris & Watts	2009	Practice testing	1.21	75	Univ	Aust		Near	Science	Surface	7 days	Normal	0.40	6

Crouse & Idstein	1972	Highlighting/ Underlining	2.909	66	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	3.26	1
Cull, W. L.	2000	Practice testing	1.414	66	Univ	USA		Near	English	Surface	< 1 day	Normal	0.66	12
Daniel & Broida	2004	Practice testing	0.975	86	Univ	USA	Control-Exp	Near	Academic	Surface	16 weeks	Normal	1.68	4
De Beni & Moè	2003	Imagery for Text	1.414	47	Univ	USA		Near	English	Surface	< 1 day	Normal	1.02	3
de Bruin, Rikers & Schmidt,	2007	Self-explanation	3.159	30	Univ	Neth		Near	Academic	Deep	14 days	Normal	0.32	4
de Croock & van Merriënboer	2007	Interleaved practice	3.047	34	Univ	Neth	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.25	12
De Croock & Van Meeienoer & Pass	1998	Interleaved practice	1.414	32	Univ	Neth	Control-Exp	Near	Engineerin g	Surface	< 1 day	Normal	-0.25	6
De Croock & Van Meeienoer & Pass	1998	Interleaved practice	1.414	32	Univ	Neth	Control-Exp	Near	Engineerin g	Deep	< 1 day	Normal	0.82	3
de Koning, Tabbers, Rikers & Paas	2011	Self-explanation	1.414	46	Sec	Neth	Control-Exp	Near	Science	Surface	< 1 day	Normal	0.22	20
Delaney & Knowles	2005	Distributed practice	5.118	128	Univ	USA	pre-post	Near	English	Surface	< 1 day	Normal	0.33	2
Dempster	1987	Distributed practice	2.909	48	Univ	USA	Exp-control	Near	English	Surface	< 1 day	Normal	1.01	3
Denis	1982	Imagery for Text	2.021	42	Univ	France	Control-Exp	Near	English	Surface	< 1 day	Normal	0.70	1
Di Vesta & Gray	1972	Summarization	2.909	10	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.49	16
Doctorow, Wittrock & Marks	1978	Summarization	2.909	488	Prim	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	1.21	15
Donovan & Radosevich	1999	Distributed practice	4.367	8990	Univ	USA	Control-Exp	Near	Academic	Surface			0.46	1
Dornisch & Sperlng	2006	Elaborative Interrogation	1.282	75	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.29	15
Duchastel & Nungester	1982	Practice testing	1.282	83	Sec	USA	Control-Exp	Near	Humanities	Surface	1 day	Normal	0.92	4
Duchastel	1981	Practice testing	3.159	57	Sec	UK		Near	Humanities	Surface	14 days	Normal	0.11	6
Durgunoglu, Mir & Ariño-Martí	1993	Re-reading	3.159	61	Univ	USA	Control-Exp	Near	English	Deep	< 1 day	Normal	0.39	10

Dyer, Riley, & Yekovich	1979	Summarization	1.282	40	Univ	USA		Near	Humanities	Surface	< 1 day	Normal	-0.10	32
Fass & Schumacher	1978	Underlining	2.909		Univ	USA		Near	Science	Surface	< 1 day	Normal	0.50	1
Fazio, Agarwal, Marsh & Roediger	2010	Practice testing	2.021	72	Univ	USA		Near	English	Surface	7 days	Normal	3.30	3
Fishman, Keller & Atkinson	1968	Distributed practice	2.909	29	Prim	USA	within-subj	Near	English	Surface		Normal	0.91	1
Foos	1995	Summarization	0.72	150	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.30	4
Foos & Fisher,	1988	Practice testing	2.909	105	Univ	USA		Near	Humanities	Surface	2 days	Normal	0.43	2
Friend	2001	Summarization	3.159	294	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.10	4
Fritz, Morris, Nolan & Singleton	2007	Practice testing	2.591	60	Pre schoo l	UK		Near	Academic	Surface	7 days	Normal	2.00	2
Fritz, Morris, Acton, Voelkel & Etkind	2007	Keyword Mnemonic	1.414	30	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.58	3
Gagne & Memory	1978	Imagery for Text	1.101	64	Prim	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	-0.02	2
Gajria & Salvia	1992	Summarization	2.943	30	Sec	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Low	1.78	7
Gambrell & Jawitz	1993	Imagery for Text	1.65	60	Prim	USA		Near	English	Surface	< 1 day	Normal	0.45	14
Glover	1989	Practice testing	2.909	60	Sec	USA	Control-Exp	Near	Science	Surface	3 days	Normal	1.91	7
Glover & Corkill	1987	Distributed practice	2.909	64	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	1.42	2
Glover, Zimmer, Filbeck, & Plake	1980	Highlighting/ Underlining	1.087	30	Univ	USA	Time series	Near	Gn knowledge	Surface	< 1 day	Normal	1.83	7
Goldstone	1996	Interleaved practice	2.021	26	Univ	USA	exp-control	Near	Academic	Surface	< 1 day	Normal	0.77	2
Goverover, Arango-Lasprilla, Hillary, Chiaravalloti, & DeLuca,	2009	Distributed practice	2.01	25	Adult	USA	within-subj	Near	English	Surface		Low	0.37	2
Goverover, Hillary, Chiaravalloti, Arango-Lasprilla, & DeLuca	2009	Distributed practice	2.464	38	Adult	USA		Near	English	Surface	5 minutes	Normal	0.44	2

Green	1990	Distributed practice	3.098	60	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.58	2
Green, Symons & Richards	1996	Elaborative Interrogation	3.159	41	Prim	Canada	Control-Exp	Near	Recall	Surface	< 1 day	Low	0.43	6
Greene	1989	Distributed practice	3.098	48	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.21	2
Griffin & Wiley	2008	Self-explanation	2.021	150	Univ	USA	Control-Exp	Near	Science	Surface	< 1 day	Normal	0.01	5
Griffin, Wiley & Thiede	2008	Re-reading	2.021	150	Univ	USA	Control-Exp	Near	Science	Surface	< 1 day	Normal	-0.04	10
Gyselinck, Meneghetti, de Beni & Pazzaglia	2009	Imagery for Text	2.158	43	Univ	Italy	Control-Exp	Near	English	Surface	< 1 day	Normal	0.92	17
Hall	1988	Keyword mnemonic	2.909	12	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.10	5
Hamilton	1997	Elaborative Interrogation	3.159	40	Univ	USA	Control-Exp	Near	Recall	Surface	< 1 day	Normal	0.32	24
Hare & Borchardt	1984	Summarization	1.65	32	Sec	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.70	18
Hartley, Bartlett & Branthwaite	1980	Highlighting/ Underlining	1.282		Prim	USA		Near	English	Surface	< 1 day	Normal	0.67	2
Hatala, Brooks & Norman	2003	Interleaved practice	2.705	71	Univ	Canada	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.66	2
Hayati & Shariatifar	2009	Highlighting/ Underlining	0	40	Univ	Iran		Far	English	Surface	< 1 day	Normal	2.16	1
Head, Readence & Buss	1989	Summarization	0	46	Sec	USA	Control-Exp	Near	Gn knowledge	Surface	7 days	Normal	-0.12	9
Helsdingen, van Gog & van Merriënboer	2011	Interleaved practice	4.071	36	Univ	Neth	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.38	6
Helsdingen, van Gog & van Merriënboer	2011	Interleaved practice	2.909	120	Univ	Neth	exp-control	Near	English	Surface	< 1 day	Normal	0.45	2
Hintzman & Rogers	1973	Distributed practice	2.021	27	Univ	USA	Control-Exp	Near	Academic	Surface	< 1 day	Normal	3.47	3
Hinze & Wiley	2011	Practice testing	2.463	69	Univ	USA	Control-Exp	Near	Science	Surface	2 days	Normal	0.48	6
Idstein & Jenkins	1972	Highlighting/ Underlining	1.282	79	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.08	2

Jacoby & Dallas	1981	Distributed practice	5.495	16	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.70	1
Jacoby, Wahlheim & Coane	2010	Practice testing	3.098	40	Univ	USA		Near	Science	Surface	< 1 day	Normal	0.59	28
Janiszewski, Noel & Sawyer	2003	Distributed Practice	2.783	1489 79	Univ	USA		Near	Words	Surface		Normal	0.72	1
Johnson & Mayer	2009	Practice testing	2.909	282	Univ	USA	Control-Exp	Near	Science	Surface	1 day	Normal	0.12	2
Johnson, L	1988	Highlighting/ Underlining	0	46	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.52	4
Kahl & Woloshyn	1994	Elaborative Interrogation	1.414	36	Prim	Canada		Far	Science	Surface	< 1 day	Normal	0.84	4
Kang & Pashler	2012	Interleaved practice	1.414	90	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.75	2
Kang, McDaniel & Pashler	2011	Practice Testing	2.986	50	Univ	USA	Control-Exp	Near	Maths	Surface	< 1 day	Normal	0.08	4
Kardash & Scholes	1995	Re-reading	3.159	61	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.53	6
Karpicke & Blunt	2011	Practice testing	34.4	40	Univ	USA	Control-Exp	Near	English	Surface	7 days	Normal	1.22	5
Karpicke & Roediger	2007a	Practice testing	3.098	48	Univ	USA		Near	English	Surface	1-2 days	Normal	1.09	8
Karpicke & Roediger	2007b	Practice testing	5.118	60	Univ	USA		Near	English	Surface	7 days	Normal	0.46	3
Keys	1934	Practice testing	2.909	268	Univ	USA		Near	Science	Surface	15 weeks	Normal	0.31	5
King	1992	Summarization	3.618	38	Univ	USA	Pre-post	Far	English	Deep	< 1 day	Normal	0.67	6
King, Biggs & Lipsky	1984	Summarization	1.101	55	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	3 days	Normal	2.00	2
Klare, Mabry & Gustafson	1955	Highlighting/ Underlining	4.367	220	Adult	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.15	2
Kornell & Bjork	2008	Distributed practice	6.501	120	Univ	USA	Control-Exp	Near	Humanities	Surface	< 1 day	Normal	0.99	3
Kornell	2009	Practice testing	1.414	20	Univ	USA		Near	English	Surface	1 day	Normal	0.92	3
Kornell, Castel, Eich & Bjork	2010	Distributed practice	2.913	64	Univ	USA	Control-Exp	Near	Humanities	Surface	< 1 day	Normal	1.00	2

Kromann, Bohnstedt, Jensen, & Ringsted	2010	Practice testing	2.705	89	Univ	Denm	Control-Exp	Near	Science	Surface	6 months	Normal	0.40	1
Kromann, Jensen, & Ringsted	2009	Practice testing	3.617	81	Univ	Denm	Control-Exp	Near	Science	Surface	14 days	Normal	0.93	1
Kulhavy & Swenson	1975	Imagery for Text	2.25	47	Prim	USA		Near	Humanities	Surface	7 days	Normal	0.29	8
Kulhavy, Dyer & Silver	1975	Summarization	1.282	144	Sec	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	-0.10	1
Lawson & Hogben	1998	Keyword Mnemonic	4.071	26	Sec	Aust	Control-Exp	Near	Languages	Surface	< 1 day	Normal	1.15	8
Leeming, F. C.	2002	Practice testing	0.975	192	Univ	USA		Near	Science	Surface	6 weeks	Normal	0.33	4
Leicht & Cashen	1971	Highlighting/ Underlining	0	82	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.12	9
Lesgold, McCormick & Golinkoff	1975	Imagery for Text	2.909	44	Prim	USA	Control-Exp	Near	English	Surface	27 days	Normal	0.77	5
Leutner, Leopold & Sumfleth	2009	Imagery for Text	3.047	111	Sec	Germ	Control-Exp	Near	English	Surface	< 1 day	Normal	0.19	1
Levin & Divine-Hawkins	1974	Imagery for Text	1.101	48	Prim	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.39	3
Levin, Pressley, McCormick, Miller & Shriberg	1979	Keyword Mnemonic	2.909	70	Sec	USA	Control-Exp	Near	Languages	Surface	< 1 day	Normal	-0.17	8
Logan & Balota	2008	Distributed practice	1.328	190	Adult	USA	Control-Exp	Near	English	Surface	1 day	Normal	1.65	2
Lorch, Lorch & Klusewitz	1995	Highlighting/ Underlining	3.159	84	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.26	3
Lyle & Crawford	2011	Practice testing	0.975	148	Univ	USA		Near	Science	Surface	12 week	Normal	1.44	1
Magliano, Trabasso & Graesser	1999	Self-explanation	2.909	23	Univ	USA		Near	English	Deep	< 1 day	Normal	1.44	1
Magliano, Trabasso & Graesser	1999	Self-explanation	2.909	38	Univ	USA		Near	English	Surface	2 days	Normal	-0.36	4
Maher & Sullivan	1982	Imagery for Text	0	78	Prim	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.02	9
Malone & Mastropieri	1991	Summarization	2.943	30	Sec	USA	Control-Exp	Near	English	Surface	< 1 day	Low	1.35	12

Marsh, Agarwal & Roediger	2009	Practice testing	2.426	32	Univ	USA		Near	Academic	Surface	< 1 day	Normal	1.65	3
Mastropieri, Scrugs & Fulk	1990	Keyword mnemonic	2.807	25	Sec	USA	Control-Exp	Near	English	Surface	< 1 day	Low	2.05	6
Matthews	2008	Self-explanation	0	121	Prim	USA	Control-Exp	Near	Mathematics	Surface	< 1 day	Normal	0.52	1
Matthews & Rittle-Johnson	2009	Self-explanation	3.353	121	Prim	USA	Control-Exp	Far	Mathematics	Deep	< 1 day	Normal	0.58	2
Mayfield & Chase	2002	Interleaved practice	1.087	66	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.74	9
McDaniel & Donnelly	1996	Elaborative Interrogation	2.909	201	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.53	1
McDaniel & Pressley	1984	Keyword Mnemonics	2.909	36	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.92	12
McDaniel, Agarwal, Huesler, McDermott & Roediger	2011	Practice testing	2.909	184	Univ	USA	Control-Exp	Near	Science	Surface	20 days	Normal	0.75	4
McDaniel, Anderson, Derbish, & Morrisette	2007	Practice testing	1.21	68	Univ	USA	Control-Exp	Near	Academic	Surface	3 weeks	Normal	0.40	8
McDaniel, Howard & Einstein	2009	Practice testing	6.501	48	Univ	USA		Near	English	Deep	< 1 day	Normal	0.62	18
McDaniel, Wildman, & Anderson	2012	Practice testing	0.921	16	Univ	USA		Near	Science	Surface	15 weeks	Normal	1.33	7
Miccinati	1982	Imagery for Text	1.101	75	Prim	USA		Far	English	Surface	< 1 day	Normal	0.49	40
Miller & Pressley	1989	Elaborative Interrogation	3.353	32	Prim	USA	Control-Exp	Near	Recall	Surface	< 1 day	Normal	0.08	13
Mitchell, Nash, & Hall	2008	Interleaved practice	3.098	24	Univ	Aust		Near	Academic	Surface	< 1 day	Normal	1.08	2
Morris & Fritz	2002	Practice testing	2.463	183	Univ	UK		Near	Academic	Surface	< 1 day	Normal	0.85	2
Neuschatz, Preston, Toglia & Neuschatz	2005	Practice testing	1.14	104	Univ	USA		Near	Academic	Surface	< 1 day	Normal	1.81	3
Nist & Hogrebe	2010	Highlighting/ Underlining	0	134	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.39	4
Nungester & Duchastel	1982	Practice testing	2.909	97	Sec	USA	Control-Exp	Near	Humanities	Deep	14 days	Normal	0.50	2

Oakhill & Patel	1991	Imagery for Text	1.192	44	Prim	UK	Control-Exp	Near	English	Surface	< 1 day	Normal	1.06	1
Olina, Reiser, Huang, Lim & Park	2006	Interleaved practice	1.414	73	Sec	USA	Control-Exp	Near	English	Surface	< 1 day	Low	-0.17	12
O'Reilly, Symons & MacLatchy-Gaudet	1998	Elaborative Interrogation	3.159	37	Univ	Canada	Control-Exp	Near	Science	Surface	< 1 day	Normal	0.63	11
O'Reilly, Symons & MacLatchy-Gaudet	1998	Self-Explanation	3.159	37	Univ	Candad	Control-Exp	Near	Science	Surface	< 1 day	Normal		3
O'Shea, Sindelar & O'Shea	1985	Re-reading	1.101	60	Prim	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	1.33	6
Ozgungor & Guthrie	2004	Elaborative Interrogation	2.909	119	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.67	1
Peterson, S. E.	1992	Highlighting/ Underlining	0	44	Univ	USA		Near	Humanities	Surface	< 1 day	Normal	-0.19	8
Pressley	1976	Imagery for Text	2.909	54	Prim	USA	Control-Exp	Near	English	Surface	< 1 day	High	0.28	6
Pressley & Levin	1978	Keyword Mnemonic	3.353	36	Prim	USA	Exp-Control	Near	Languages	Surface	< 1 day	Normal	0.00	6
Pressley, McDaniel, Turnure, Wood & Ahmad	1987	Elaborative Interrogation	3.098	240	Univ	Canada	Control-Exp	Near	Recall	Surface	< 1 day	Normal	0.54	4
Pyc & Rawson	2010	Practice testing	34.4	118	Univ	USA	Control-Exp	Near	Languages	Surface	7 days	Normal	4.33	3
Pyc, & Dunlosky	2010	Distributed practice	2.021	68	Univ	USA	Control	Near	English	Surface	< 1 day	Normal	0.74	16
Pyc, & Rawson	2012	Practice testing	3.098	53	Univ	USA	Control	Near	Languages	Surface	2 days	Normal	0.89	2
Pyc, & Rawson	2014	Distributed practice	3.098	53	Univ	USA	Control	Near	Languages	Surface	2 days	Normal	0.68	9
Ramsay, Sperling & Dornisch	2010	Elaborative Interrogation	1.96	234	Univ	USA	Control-Exp	Near	Humanities	Surface	< 1 day	Normal	-0.11	2
Rasco, Tennyson & Boutwell	1975	Imagery for Text	2.909	91	Univ	USA	Exp-control	Near	English	Surface	< 1 day	Normal	0.57	2
Rau, Aleven & Rummel	2010	Interleaved practice	0	108	Prim	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Low	-0.32	12
Raugh & Atkinson	1975	Keyword Mnemonic	2.909	40	Univ	USA	Control-Exp	Near	Languages	Surface	< 1 day	Normal	0.03	3
Rawson & Kintsch	2005	Re-reading	2.909	79	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.38	1

Rawson & Kintsch	2005	Re-reading	2.909	168	Univ	USA	Control-Exp	Near	English	Surface	2 days	Normal	0.28	14
Rawson	2012	Re-reading	5.118	187	Univ	USA	Exp-control	Near	Humanities	Surface	< 1 day	Normal	0.32	10
Rawson & Dunlosky	2011	Practice testing	5.495	130	Univ	USA		Near	Science	Surface	2 days	Normal	0.53	16
Rawson & Kintsch	2005	Distributed practice	2.909	77	Univ	USA	Control	Near	English	Surface	2 days	Normal	0.31	12
Rewey, Dansereau, & Peel	1991	Summarization	3.159	47	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.11	14
Reynolds & Glaser	1964	Distributed practice	2.909	150	Sec	USA	Control-Exp	Near	Science	Surface	< 1 day	Normal	0.63	4
Riches, Tomasello & Conti-Ramsden	2005	Distributed practice	2.68	48	Prim	UK	Control-Exp	Near	English	Surface	< 1 day	Low	0.22	4
Rickards & Denner	1979	Highlighting/ Underlining	1.96	21	Prim	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	-0.24	8
Rinehart, Stahl, & Erickson,	1986	Summarization	1.65	60	Prim	USA	Control-Exp	Near	Gn knowledge	Surface	2 days	Normal	0.54	4
Rittle-Johnson	2006	Self-Explanation	4.235	85	Prim	USA	Control-Exp	Near	Maths	Surface	< 1 day	Normal	0.52	4
Rittle-Johnson	2006	Self-Explanation	4.235	85	Prim	USA	Control-Exp	Near	Maths	Deep	< 1 day	Normal	0.06	8
Roediger & Karpicke,	2011	Practice testing	6.501	120	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.53	7
Roediger & Marsh	2005	Practice testing	3.098	24	Univ	USA		Near	English	Surface	< 1 day	Normal	3.20	1
Rohrer & Taylor	2006	Distributed practice	1.414	116	Univ	USA	Control-Exp	Near	Mathematic s	Surface	28 days	Normal	0.41	2
Rohrer & Taylor	2007	Interleaved practice	1.96	66	Univ	USA	Control-Exp	Near	Mathematic s	Surface	7 days	Normal	1.20	2
Rohrer, Taylor & Sholar	2010	Practice testing	3.098	28	Prim	USA	Control-Exp	Near	Humanities	Surface	1 day	Normal	-0.25	6
Ross, & Di Vesta,	1976	Summarization	2.909	52	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	7 days	Normal	0.06	4
Runquist	1983	Practice testing	2.021	42	Univ	Canada	Exp-control	Near	English	Surface	< 1 day	Normal	0.91	4
Schmidmaier, Ebersbach, Schiller, Hege, Hlozer & Fischer	2011	Practice testing	3.617	80	Univ	Germ		Near	English	Surface	7 days	Normal	0.38	2
Schworm & Renkl	2006	Self-explanation	3.242	40	Univ	Germ	Control-Exp	Near	English	Surface	< 1 day	Normal	0.57	10

Seabrook, Brown & Solity	2005	Distributed practice	1.414	40	Prim	UK	Control-Exp	Near	Mathematics	Surface	< 1 day	Normal	0.91	1
Seifert	1993	Elaborative Interrogation	2.909	55	Sec	Canada	Control-Exp	Near	Recall	Surface	< 1 day	Normal	0.21	24
Shapiro, & Waters	2005	Imagery for Text	1.358	56	Univ	USA		Near	Languages	Surface	< 1 day	Normal	2.98	2
Shriberg, Levin, McCormick, & Pressley	1982	Keyword Mnemonic	2.909	48	Sec	Canada	Exp-Control	Near	Languages	Surface	< 1 day	Normal	0.00	7
Smith, Holliday & Austin	2010	Elaborative Interrogation	3.02	147	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.37	6
Smith & Kimball	2010	Practice testing	3.098	103	Univ	USA	within-subj	Near	Gn knowledge	Surface	< 1 day	Normal	0.15	2
Smith & Kimball	2010	Distributed Practice	3.098	103	Univ	USA	Within Subject	Near	General Knowledge	Surface	< 1 day	Normal	0.15	2
Sobel, Cepeda & Kapler	2011	Distributed practice	1.414	38	Prim	Canada	Control-Exp	Near	English	Surface	7 days	Normal	0.91	1
Spörer, Brunstein, & Kieschke	2009	Summarization	4.071	84	Prim	Germ	Control-Exp	Near	Gn knowledge	Surface	12 week	Normal	0.29	6
Spurlin, Dansereau, O'Donnell & Brooks	1988	Summarization	0.72	32	Univ	USA		Near	Science	Surface	5 days	Normal	0.77	4
Stein & Bransford	1979	Elaborative Interrogation	5.118	60	Univ	USA	Control-Exp	Near	Recall	Surface	< 1 day	Normal	1.94	2
Sumowski, Chiaravalloti & DeLuca	2010	Practice testing	3.425	16	Adult	USA	within-subj	Near	English	Surface	< 1 day	Normal	0.69	3
Taylor & Rohrer	2010	Interleaved practice	1.414	24	Prim	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	1.21	1
Thiede & Anderson	2003	Summarization	3.159	52	Univ	USA	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	0.38	8
Thomas & Wang	1996	Keyword Mnemonic	2.426	56	Univ	USA	Control-Exp	Near	Languages	Surface	< 1 day	Normal	-0.41	8
Toppino	1991	Distributed practice	2.021	46	Pre school	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.95	6
Toppino, & Cohen	2009	Practice testing	1.95	12	Univ	USA	exp-control	Near	English	Surface	2 days	Normal	1.30	2

Toppino, Fearnow-Kenney, Kieper, & Teremula	2009	Distributed practice	2.021	144	Prim	USA	Control-Exp	Near	Academic	Surface	< 1 day	Normal	0.62	12
Tse, Balota & Roediger	2010	Practice testing	2.913	64	Adult	USA		Near	Academic	Surface	< 1 day	Normal	0.32	4
van Hell & Mahn	1997	Keyword Mnemonic	1.433	36	Univ	Neth	Control-Exp	Near	Gn knowledge	Surface	< 1 day	Normal	-0.55	24
van Merriënboer, Schuurman, de Croock, & Paas	2002	Interleaved practice	4.071	69	Univ	Neth	Control-Exp	Near	Science	Surface	< 1 day	Normal	-0.02	12
Verkoeijen, Rikers, & Özsoy	2008	Distributed practice	1.414	38	Univ	Neth	Exp-control	Near	Humanities	Surface	2 days	Normal	0.70	5
Vlach, Sandhofer & Kornell	2008	Distributed practice	5.088	36	Pre schoo l	USA	Control-Exp	Near	Academic	Surface	< 1 day	Normal	2.88	1
Vojdanoska, Cranney, & Newell	2010	Practice testing	1.414	106	Univ	Aust	Control-Exp	Near	Science	Surface	6 weeks	Normal	1.03	2
Wahlheim, Dunlosky & Jacoby	2011	Interleaved practice	2.021	48	Univ	USA	Control-Exp	Near	Academic	Surface	< 1 day	Normal	0.87	4
Wahlheim, Dunlosky & Jacoy	2010	Distributed practice	2.021	48	Univ	USA	Control-Exp	Near	Science	Surface	< 1 day	Normal	1.19	3
Wang & thomas	1995	Keyword Mnemonic	2.909	34	Univ	USA	Control-Exp	Near	English	Surface	< 1 day	Normal	0.81	10
Wang, Thomas, & Ouellette	1992	Keyword Mnemonic	2.909	79	Univ	USA	Exp-control	Near	Languages	Surface	< 1 day	Normal	1.32	6
Weinstein, McDermott, & Roediger	2010	Practice testing	2.426	29	Univ	USA	Within-subj	Near	Academic	Surface	< 1 day	Normal	0.95	6
Wenger, Thompson, & Bartling	1980	Practice testing	0	64	Univ	USA	Exp-Control	Near	English	Surface	2 days	Normal	0.97	2
Wheeler, Ewers, & Buonanno	2003	Practice testing	2.463	60	Univ	USA	Exp-Control	Near	English	Surface	2 days	Normal	0.39	3
Willoughby & Wood	1994	Elaborative Interrogation	4.071	32	Univ	Canada	Control-Exp	Near	Recall	Surface	< 1 day	Normal	0.81	2
Willoughby, Waller, Wood & McKinnon	1993	Elaborative Interrogation	3.159	40	Univ	Canada	Control-Exp	Near	Recall	Surface	< 1 day	Normal	1.40	4

Willoughby, Waller, Wood & McKinnon	1993	Elaborative Interrogation	3.159	40	Univ	Canada	Control-Exp	Near	Recall	Surface	28 days	Normal	1.39	2
Woloshyn, Pressley & Schneider	1992	Elaborative Interrogation	2.909	30	Univ	Canada	Control-Exp	Near	Humanities	Surface	< 1 day	Normal	2.72	4
Woloshyn, Pressley & Schneider	1992	Elaborative Interrogation	2.909		Univ	Germ	Control-Exp	Near	Humanities	Surface	< 1 day	Normal	1.51	4
Woloshyn, & Stockley	1995	Elaborative Interrogation	1.414	40	Sec	Canada		Near	Science	Surface	< 1 day	Normal	0.72	12
Woloshyn, Paivio & Pressley,	1994	Elaborative Interrogation	2.909	60	Sec	Canada		Far	Science	Surface	< 1 day	Normal	0.95	48
Woloshyn, Willoughby, Wood, & Pressley,	1990	Elaborative Interrogation	2.909	36	Univ	Canada		Near	Academic	Surface	< 1 day	Normal	1.20	14
Wong, Lawson & Keeves	2002	Self-explanation	4.071	47	Sec	Aust	Control-Exp	Near	Mathematic s	Surface	< 1 day	Normal	0.72	14
Wood & Hewitt	1993	Elaborative Interrogation	1.158	35	Prim	Canada	Control-Exp	Near	English	Surface	< 1 day	Low	0.86	2
Wood, Pressley, & Winne	1990	Imagery for Text	2.909	36	Sec	Canada		Near	Gn knowledge	Surface	< 1 day	Normal	1.01	6
Wood, Miller, Symons, Canough & Yedlicka	1993	Elaborative Interrogation	1.51	120	Pre schoo l	USA	Control-Exp	Near	Recall	Surface	< 1 day	Normal	0.28	32
Wood, Willoughby, Bolger, Younger & Kaspar	1993	Elaborative Interrogation	3.353	40	Prim	Canada	Control-Exp	Near	Recall	Surface	< 1 day	Low	0.64	3
Zaromb & Roediger	2010	Practice testing	2.021	36	Univ	USA	Control-Exp	Near	Recall	Surface	2 days	Normal	0.74	8

Appendix 3: Chapter 6 Hattie & Donoghue – Meta-Synthesis Summary Table.

No.	Study Author(s)	Influence	No. studies	No. people	No. effects	ES
Prior achievement						
1	Duncan et al. (2007)	Pre-school to first years of schooling	6		228	0.35
2	Ernst (2001)	Early cognition and school achievement	23	1,733	32	0.41
3	Kuncel, Hezlett & Ones (2001)	High school grades to university grades	1,753	82,659	6,589	0.52
4	Kavale & Nye (1985)	Ability component in predicting special ed students	1,077		268	0.68
5	Piburn (1993)	Prior ability on science achievement	44		186	0.80
6	Trapmann, Hell, Weigand, & Schuler (2007)	High school grades to university grades	83		83	0.90
7	Schuler, Funke, & Baron-Boldt (1900)	High school grades to university grades	63	29,422	63	1.02
8	Boulanger (1981)	Ability related to science learning	34		62	1.09
9	Hattie & Hansford (1983)	Intelligence and achievement	72		503	1.19

Working memory						
10	Carretti, Borellam Cornoldi, & de Beni (2009(	Working memory on achievement	18	3,922	18	0.71
11	van den Bos, van den Ven, Kroesbergen, & van Luit (2013)	Working memory on achievement	111	16,921	1,233	0.70
	Will					
	Self-efficacy					
12	Dignath et al. (2008)	Self-efficacy	13		13	1.84
13	Robbins, Lauver, Le, Davis, Langley, & Carlstrom (2004)	Academic self-efficacy	18	9,598	18	0.82
14	Holden, Moncher, Schinke, & Barker (1990)	Self-efficacy	25		26	0.37
15	Multon, Brown, & Lent (1991)	Self-efficacy	36	4,998	38	0.76
16	Carpenter (2007)	Self-efficacy	48	12,466	48	0.70
	Self-concept					
17	Hansford & Hattie (1980)	Self-concept	128	202,823	1,136	0.41
18	Muller, Gullung, & Bocci (1988)	Self-concept	38		838	0.36
19	Wickline (2003)	Self-concept	41	48,038	41	0.35
20	Valentine, DuBois, & Cooper (2004)	Self-concept	56	50,000	34	0.32
21	O'Mara & Marsh (2006)	Self-concept interventions	145		460	0.51
22	Huang (2011)	Self-concept	32	44,594	39	0.49
Reducing anxiety						
23	Kim et al. (2008)	Lowering text anxiety	4		9	1.10
24	Hembree (1988)	Reduced test anxiety	46	28,276	176	0.22

25	Harris (1987)	Reduced anxiety on performance	70		70	0.35
26	Seipp (1991)	Reduction of anxiety on achievement	26	36,626	156	0.43
27	Bourhis & Allen (1992)	Lack of communication apprehension	23		728	0.37
28	Taylor (1995)	Reducing anxiety in math	25	22,189	47	0.31
29	Fitzgerald (1996)	Reducing anxiety to statistics	27		82	0.28
30	Ma (1999)	Reducing anxiety towards math and achievement	26	18,279	37	0.56
Task value						
31	Dignath et al. (2008)	Task value	6		6	0.46
	Attitude to content					
32	Willson (1983)	Attitudes to science	43	638,333	280	0.32
33	Bradford (1991)	Attitude to mathematics	102		241	0.29
34	Ma & Kishor (1997)	Attitude to mathematics	143	94,661	143	0.47
35	Petscher (2010)	Attitude to reading and achievement	32	224,615	118	0.32
Incremental vs entity thinking						
36	Burnette, O’Boyle, van Epps, Pollack, & Finkel (2013)	Incremental vs entity thinking	85	28,217	113	0.19
	Mindfulness					
37	Zenner, Hermeben-Kurz, & Walach (2014)	Mindfullness on achievement	24	1,348	24	0.41

38	Sedlmeier, Eberth, Schwarz, Zimmerman, Haarig, Jaeger, & Kunze (2012)	Mindfullness on achievement	22	1,502	22	0.23
39	Zoogman, Goldberrg, Hoyt, & Miller (2014)	Mindfullness on achievement	20	1,772	138	0.23
Thrill **Surface approach**						
40	Purdie & Hattie (1999)	Surface approach	101		101	0.10
41	Hulleman, Schrager, Bodmann, & Harackiewica (2010)	Approach goals on achievement	243	91,087	243	0.12
	Surface motivation					
42	Purdie & Hattie (1999)	Surface motivation	48		48	-0.54
43	van Yperen, Blaga, & Postmes (2014)	Performance goals on achievement	98		106	0.20
44	Rolland (2012)	Performance goals on achievement	10		10	-0.22
Deep approach						
45	Purdie & Hattie (1999)	Deep approach	38		38	0.63
Deep motivation						
46	Purdie & Hattie (1999)	Deep motivation	72		72	0.75
Achieving approach						
47	Purdie & Hattie (1999)	Achieving approach	95		95	0.70

Achieving motivation						
48	Purdie & Hattie (1999)	Achieving motivation	18		18	0.18
Mastery goals (general)						
49	van Yperen, Blaga & Postmes (2014)	Mastery goals on achievement	98		103	0.28
50	Rolland (2012)	Mastery goals on achievement	12		12	0.04
51	Carpenter (2007)	Mastery goals on achievement	48	12,466	48	0.24
Goals (mastery, performance, social)						
52	Robbins, Lauver, Le, Davis, Langley, & Carlstrom (2004)	Achievement goals	34	17,575	34	0.65
53	Uguroglu & Walberg (1979)	Motivation	40	36,946	232	0.34
54	Findley & Cooper (1983)	Internal locus of control	98	15,285	275	0.36
55	Whitley & Frieze (1985)	Success vs failure attributions	25		25	0.56
56	Schiefel, Krapp, & Schreyer (1995)	Interest and achievement	21		121	0.65
57	Kalechstein & Nowicki (1997)	Internal locus of control	78	58,142	261	0.23
58	Crede & Phillips (2011)	Motivation strategies	67	19,900	2,158	0.24
59	Wagner & Szamoskozi (2012)	Direct academic motivation training	17	3,720	17	0.33
60	Marzano (2000)	Goal specification	53		53	0.97
61	Cerasoli, Nicklin, & Ford (2014)	Intrinsic motivation	125	196,778	125	0.47
62	Chen, Chen, & Zhu (2013)	Motivation on physical education outcomes	29		283	0.43

Management of the Environment Environmental structuring						
63	Lavery (2008)	Environmental restructuring	4		4	0.22
64	Donker et al. (2013)	Environmental restructuring	6		6	0.59
Time management						
65	Lavery (2008)	Time management	8		8	0.44
66	Kyriakides, Christoforou, & Charalambous	Time management	78		78	0.35
	Social support					
67	Robbins, Lauver, Le, Davis, Langley, & Carlstrom (2004)	Social support	33	12,366	33	0.12
Student control over learning						
68	Niemiec, Sikorski, & Walberg (1996)	Student control over learning in CAI	24		24	-0.03
69	Patall, Cooper, & Robinson (2008)	Control over learning on subsequent control	41		14	0.10
70	Karich, Bruns, & Maki (2014)	Contol over learning in CAI	18	3,618	29	0.05
71	Parsons (1992)	Control over learning in CAI	41	4,375	94	-0.04
Time of day to study						
72	Preckel, Lipnevich, Schneider, & Roberts (2011)	Preference for morning over afternoon for intensive study	19	3,920	19	0.02

73	Richardson, Abraham, & Bond (2012)	Preference for morning over afternoon for intensive study	217		1,105	0.06
74	Tonetti, Natale, & Randler (2015)	Preference for morning over afternoon for intensive study	31	27,309	31	0.29
			Background music			
75	Kampfe, Sedlmeier, & Renkewit (2010)	Background music	43	3,104	43	-0.04
			Sleep			
76	Dewald, Meijer, Oort, Kerkhof, & Bogels (2010)	Sleep quality, duration & sleepiness	26	48,360	26	0.01
77	Astill, van der Heijden, van Ijzendoorn, & van Someren (2013)	Sleep on achievement	52	24,454	52	0.12
78	Galland, Spruyt, Dawes, McDowall, Elder, & Schaughency (2013)	Sleep on achievement	18		18	-0.29
			Exercise			
79	Moon, Render, & Pendley (1985)	Relaxation and achievement	20		36	0.16
80	Etnier, Salazar, Landers, Petruzzelo, Han, & Nowell (1997)	Physical fitness & exercise	134		1,260	0.25
81	Sibley & Etnier (2002)	Physical activity on achievement	36		104	0.36
82	Etnier, Nowell, Landers, & Sibley (2006)	Aerobic fitness and cognitive performance	37	1,306	571	0.34

83	Verburgh, Lonigs, Scherder, & Oosterlaan (2014)	Physical activity on executive functioning	19	586	19	0.52
84	Fedewa & Ahn (2011)	Physical activity on achievement	59	28,314	195	0.32
85	Hattie & Clinton (2012)	Physical activity on achievement	13		80	0.03
86	Chang, Labbam, Gapin, & Etnier (2012)	Physical activity on achievement	79		79	0.10
Success Criteria **Advance organisers**						
87	Marzano (2000)	Advance organisers	358		358	0.48
88	Kozlow & White (1978)	Advance organisers	77		91	0.89
89	Luiten, Ames, & Ackerman (1980)	Advance organisers	135		160	0.21
90	Stone (1983)	Advance organisers	29		112	0.66
91	Lott (1983)	Advance organisers in science	16		147	0.24
92	Asencio (1984)	Behavioural objectives	111		111	0.12
93	Klauer (1984)	Intentional learning	23		52	0.40
94	Rolhelser-Bennett (1987)	Advance organisers	12	1,968	45	0.80
95	Mahar (1992)	Advance organisers	50		50	0.44
96	Catts (1992)	Incidental learning	14		80	-0.03
97	Catts (1992)	Intentional learning	90		1,065	0.35
98	Preiss & Gayle (2006)	Advance organisers	20	1,937	20	0.46
Setting standards for self-judgement						
99	Lavery (2008)	Setting standards for self-judgement	156		156	0.62

Planning and prediction						
100	Dignath et al. (2008)	Planning and prediction	68		68	0.80
101	Marzano (2000)	Information specification/ predictions	242		242	0.38
102	Donker et al. (2013)	Planning	68		68	0.80
103	Kim et al. (2008)	Planning	21		42	1.04
Worked examples						
104	Crissman (2006)	Worked examples on achievement	62	3,324	151	0.57
105	Wittwer & Renkl (2010)	Worked examples	21		28	0.16
Success criteria						
106	Marzano (1998)	Cues/brief overview of success	7		7	1.13
Goal difficulty						
107	Chidester & Grigsby (1984)	Goal difficulty	21	1,770	21	0.44
108	Tubbs (1986)	Goal difficulty, specificity and feedback	87		147	0.58
109	Mento, Steel, & Karren (1987)	Goal difficulty	70	7,407	118	0.58
110	Wood, Mento, & Locke (1987)	Goal difficulty	72	7,548	72	0.58
111	Wood, Mento, & Locke (1987)	Goal specificity	53	6,635	53	0.43
112	Wright (1990)	Goal difficulty	70	7,161	70	0.55
113	Burns (2004)	Degree of challenge	55		45	0.82

Goal commitment						
114	Donovan & Radosevich (1998)	Goal commitment	21	2,360	21	0.36
115	Klein, Wesson, Hollenbeck, & Alge (1999)	Goal commitment	74		83	0.47
Goal intentions						
116	Gollwitzer & Sheeran (2007)	Goal intentions on achievement	63	8,461	94	0.72
117	Fuchs & Fuchs (1986)	Long vs short term goals	18		96	0.64
Surface Acquiring **Outlining & transforming**						
118	Lavery (2008)	Outlining & transforming	89		89	0.85
Organising						
119	Donker et al. (2013)	Organisation	32		32	0.81
120	Dignath, Buettner, & Langfeldt (2008)	Organisation	50		50	0.75
121	Purdie & Hattie (1999)	Organisation	22		22	0.23
	Record keeping					
122	Lavery (2008)	Record keeping	46		46	0.59
123	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013))	Reviewing records	131		131	0.49

Summarisation						
124	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Summarisation	20	1,914	157	0.57
125	Dignath, Buettner, & Langfeldt (2008)	Summarisation	50		50	0.75
Underlining & highlighting						
126	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Underlining	16	2,070	44	0.50
Note taking						
127	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Note taking	5	447	49	0.45
128	Purdie & Hattie (1999)	Note taking	40		40	0.44
129	Henk & Stahl (1985)	Note taking	21		25	0.34
130	Kobayashi (2005)	Note taking	57		131	0.22
131	Larwin & Larwin (2013)	Guided notes	12	1,529	27	0.55
132	Larwin, Gorman, & Larwin (2013)	Testing aids (notes, crib sheets, text books)	15	3,146	15	0.99
133	Marzano (1994)	Note taking	36			
Mnemonics						
134	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Mnemonics	21	1,007	87	0.34
135	Runyan (1987)	Mnemonics	32	3,698	51	0.64
136	Kim et al. (2008)	Mnemonics	8		14	0.45

137	Mastropieri & Scruggs (1989)	Mnemonics	19		19	1.62
Strategy to integrate with prior knowledge						
138	Kim et al. (2008)	Strategy to integrate with prior knowledge	10		12	0.93
Imagery						
139	Lavery (2008)	Imagery	12	991	59	0.45
Working memory training						
140	Melby-Lervag & Hulme (2013)	Working memory training	23		30	0.35
141	Linck, Osthus, Koeth, & Bunting (2014)	Working memory training	79	3,707	748	0.41
142	Daneman & Merikle (1996)	Working memory training	77	6,179	150	0.82
Surface Consolidation **Reviewing records**						
143	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Re-reading	8	523	84	0.49
Practice testing						
144	Kulik, Kulik, & Bangert (1984)	Practice testing	19		19	0.42
145	Fuchs & Fuchs (1986)	Examiner familiarity effects	22	1,489	34	0.28
146	Bangert-Drowns, Kulik, & Kulik (1991)	Frequent testing	35		35	0.23

147	Gocmen (2003)	Frequent testing	78		233	0.40
148	Hausknecht, Halpert, Di Paolo, & Moriarty-Gerrard (2007)	Practice and retesting effects	107	134,436	107	0.26
149	Haynie (2007)	Testing on retention learning	8		27	0.66
150	Basol & Johanson (2009)	Frequency of testing	78		118	0.46
151	Phelps (2012)	Effects of testing	177	7,000,000	640	0.55
152	Rowland (2014)	Effects of testing	61		159	0.50
153	Adesope (2013)	Effects of pre-testing	89	11,700	226	0.63
Spaced vs mass practice						
154	Lee & Genovese (1988)	Spaced vs massed practice	52		52	0.96
155	Donovan & Radosevich (1999)	Spaced vs massed practice	63		112	0.46
156	Janiszewski, Noel, & Sawyer (2003)	Spaced vs massed practice	61		484	0.72
157	Cepeda, Pashler, Vul, Wixted, & Rohrer (2009)	Spaced vs massed practice	184	14,811	317	0.27
Rehearsal and memorisation						
158	Lavery (2008)	Rehearsal and memorisation	99		99	0.57
159	Donker et al. (2013)	Rehearsal (Playing flashcards to learn new word)	10		10	1.39
160	Purdie & Hattie (1999)	Memorisation	23		23	0.23
161	Rolhelser-Bennett (1987)	Working memory training	12	1,968	78	1.28
162	Melby-Lervag & Hulme (2013)	Working memory training	23		30	0.35

163	Linck, Osthus, Koeth, & Bunting (2014)	Working memory training	79	3,707	748	0.41
164	Daneman & Merikle (1996)	Working memory training	77	6,179	150	0.82
165	Bos, Ven, Krosebergen, & Luit (2013)	Working memory on math achievement	68		288	0.62
166	Carretti, Borella, Cornoldi, & de Beni (2009)	Working memory on reading achievement	19	1,613	19	0.71
Teaching test taking & coaching						
167	Messick & Jungeblut (1981)	Coaching for SAT	12		12	0.15
168	Bangert-Drowns, Kulik, & Kulik (1983)	Training in test taking skills	30		30	0.25
169	DerSimonian & Laird (1983)	Coaching on the SAT-M/V	36	15,772	36	0.07
170	Samson (1985)	Training in test taking skills	24		24	0.33
171	Scruggs, White, & Bennion (1986)	Training in test taking skills	24		65	0.21
172	Kalaian & Becker (1986)	Coaching for SAT	34		34	0.34
173	Powers (1986)	Coaching for college admission	10		44	0.21
174	Becker (1990)	Coaching for SAT	48		70	0.30
175	Witt (1993)	Training in test taking skills	35		35	0.22
176	Kulik, Bangert-Drowns, & Kulik (1994)	Coaching for SAT	14		14	0.15
177	Haynie (2007)	Test taking on retention learning	8		8	0.76

Interleaved practice						
178	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Interleaved practice	12	989	65	0.21
Effort						
179	Donker et al. (2013)	Effort	15		15	0.77
Time on task						
180	Purdie & Hattie (1999)	Time on Task	36		36	0.24
181	Bloom (1976)	Time on task	11		28	0.75
182	Fredrick (1980)	Time on task	35		35	0.34
183	Marzano (2000)	Time on task	15		15	0.39
184	Catts (1992)	Time on task	18		37	0.19
185	Shulruf, Keuskamp, & Timperley (2006)	Taking more coursework	36		36	0.24
186	Cook, Levinson, & Garside (2010)	Time on task	13		14	1.25
187	Crede, Roch, & Kieszczynka (2010)	Class attendance	90	28,034	99	0.95
Deliberate practice						
188	Macnamara, Hambrick, & Oswald (2014)	Deliberate practice	88	11,135	88	0.43
189	Platz, Kopiez, Lehmann, & Wolf (2014)	Deliberate practice	13	788	157	0.35
190	Feltz & Landers (1983)	Mental practice on motor skill learning	60	1,766	13	1.54

Giving/receiving feedback					146	0.48
191	Lysakowski & Walberg (1980)	Classroom reinforcement	39	4,842	102	1.17
192	Wilkinson (1981)	Teacher praise	14		14	0.12
193	Walberg (1982)	Cues, and reinforcement	19		19	0.81
194	Lysakowski & Walberg (1982)	Cues, participation and corrective feedback	54	15,689	94	0.97
195	Yeany & Miller (1983)	Diagnostic feedback in college science	49		49	0.52
196	Schmmel (1983)	Feedback from computer instruction	15		15	0.47
197	Getsie, Langer, & Glass (1985)	Rewards and punishment	89		89	0.14
198	Skiba, Casey, & Center (1985)	Nonaversive procedures	35		315	0.68
199	Menges & Brinko (1986)	Student evaluation as feedback	27		31	0.44
200	Rummel & Feinberg (1988)	Extrinsic feedback rewards	45		45	0.60
201	Kulik & Kulik (1988)	Timing of feedback	53		53	0.33
202	Tenenbaum & Goldring (1989)	Cues, and reinforcement	15	522	15	0.72
203	L'Hommedieu, Menges, & Brinko (1990)	Feedback from college student ratings	28	1,698	28	0.34
204	Bangert-Drowns, Kulik, Kulik, & Morgan (1991)	Feedback from tests	40		58	0.26
205	Wiersma (1992)	Intrinsic vs extrinsic rewards	20	865	17	0.50
206	Travlos & Pratt (1995)	Knowledge of results	17		17	0.71
207	Azevedo & Bernard (1995)	Computer presented feedback	22		22	0.80
208	Standley (1996)	Music as reinforcement	98		208	2.87

209	Kluger & DeNisi (1996)	Feedback	470	12,652	470	0.38
210	Neubert (1998)	Goals plus feedback	16	744	16	0.63
211	Swanson & Lussier (2001)	Dynamic assessment (feedback)	30	5,104	170	1.12
212	Miller (2003)	Corrective feedback on learning	8		8	1.08
213	Baker & Dwyer (2005)	Field independent vs field dependent	11	1,341	122	0.93
214	Witt, Wheeless, & Aooen (2006)	Immediacy of teacher feedback	81	24,474	81	1.15
215	Dragon (2009)	Field independent vs field dependent	35	3,082	35	0.43
216	Kleij, Feskens, & Eggen (2015)	Feedback in CAI	40	4,266	28	0.74
217	Lyster & Saito (2010)	Oral feedback on learning	15		70	0.42
218	Li (2010)	Corrective feedback on learning	28		28	0.61
Help seeking						
219	Lavery (2008)	Help seeking	62		62	0.60
Deep Acquiring						
Meta-cognitive strategies						
220	Haller, Child, & Walberg (1988)	Metacognitive training programs in reading	20	1,553	20	0.71
221	Chiu (1998)	Metacognitive interventions in reading	43	3,475	123	0.67

222	Donker, de Boer, Dignath, Kostons, & Werf (2013)	Learning strategies on achievement	58		180	0.66
223	Jacob & Parkinson (2015)	Executive functioning	67	15,879	291	0.36
224	Kyriakides, Christoforou, & Charalambous (2013)	Learning strategies on achievement	167	1,182,117	167	0.63
Elaboration & organisation						
225	Donker et al. (2013)	Elaboration	50		50	0.75
Concept mapping						
226	Marzano (1994)	Idea representation	708		708	0.69
227	Moore & Readence (1984)	Graphics organisers in mathematics	161		161	0.22
228	Vazquez & Carballo (1993)	Concept mapping in science	17		19	0.57
229	Horton, McConney, Gallo, Woods, Senn, & Hamelin (1993)	Concept mapping in science	19	1,805	19	0.45
230	Kang (2002)	Graphics organisers in reading with learning disabled	14		14	0.79
231	Kim, Vaughn, Wanzek, & Wei (2004)	Graphics organisers in reading	21	848	52	0.81
232	Nesbit & Adesope (2006)	Concept and knowledge maps	55	5,818	67	0.55
233	Campbell (2009)	Concept making in all subjects	38		46	0.79
234	Dexter & Hughes (2011)	Graphic organisers with learning disabled	16	808	55	0.91
Elaborative-interrogation						
235	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Elaborative-interrogation	24	2,150	164	0.42

Strategy monitoring						
236	Donker et al. (2013)	Monitoring & control	81		81	0.71
Self-regulation						
237	Ragosta (2010)	Self-regulation with college students	55	6,669	93	0.71
238	Benz (2010)	Self-regulated interventions	44	4,047	44	0.45
239	Lavery (2008)	Self-regulated learning	30	1,937	223	0.69
240	Dignath, Buettner, & Langfeldt (2008)	Self-regulation strategies	30	2,364	263	0.66
241	Benz & Schmitz (2009)	Self-regulated learning	28	4,047	28	0.37
242	Sitzmann & Ely (2011)	Self-regulation strategies	369	90,380	855	0.26
Deep Consolidating						
Evaluation and reflection						
243	Donker et al. (2013)	Evaluation & reflection	54		54	0.75
Via becoming a teacher (peer tutoring)						
244	Hartley (1977)	Effects on tutees in math	29		50	0.63
245	Hartley (1977)	Effects on tutors in math	29		18	0.58
246	Cohen, Kulik, & Kulik (1982)	Effects on tutees	65		52	0.40
247	Cohen, Kulik, & Kulik (1982)	Effects on tutors	65		33	0.33
248	Phillips (1983)	Tutorial training of conservation	302		302	0.98
249	Cook, Scruggs, Mastropieri, & Casto (1995)	Handicapped as tutors	19		49	0.53
250	Cook, Scruggs, Mastropieri, & Casto (1995)	Handicapped as tutees	19		25	0.58
251	Mathes & Fuchs (1991)	Peer tutoring in reading	11		74	0.36

252	Batya, Vaughn, Hughes, & Moody (2000)	Peer tutoring in reading	32	1,248	216	0.41
253	Elbaum, Vaughn, Hughes, & Moody (2000)	One-one tutoring programs in reading	29	325	216	0.67
254	Rohrbeck, Ginsburg-Block, Fantuzzo, & Miller (2003)	Peer assisted learning	90		90	0.59
255	Erion (2006)	Parent tutoring children	32		32	0.82
256	Ginsburg-Block, Rohrbeck, & Fantuzzo (2006)	Peer-assisted learning	28		26	0.35
257	Leung (2014)	Peer tutoring	72	15,517	72	0.39
258	Kunsch, Jitendra, & Sood (2007)	Peer mediated instruction in math with LD students	17	1,103	17	0.47
Self-verbalisation & self-questioning						
259	Dunlosky, Rawson, Marsh, Nathan, & Willingham (2013)	Self-verbalisation & Self-questioning	113	3,098	1,150	0.64
260	Rock (1985)	Special ed self-instructional training	47	1,398	684	0.51
261	Duzinski (1987)	Self-verbalising instruction training	45		377	0.84
262	Huang (1991)	Student self-questioning	21	1,700	89	0.58
Self-monitoring						
263	Lavery (2008)	Self-monitoring	154		154	0.45
Self-verbalising the steps in a problem						
264	Lavery (2008)	Self-verbalising the steps in a problem	124		124	0.62
265	Marzano (2000)	Process specification & monitoring	15		15	0.30

266	Marzano (2000)	Dispositional monitoring	15		15	0.30
Self-consequences						
267	Lavery (2008)	Self-consequences	75		75	0.70
Self-explanation						
268	Lavery (2008)	Self-explanation	8	533	69	0.50
Seeking help from peers						
269	Dignath, Buettner, & Langfeldt (2008)	Seeking help from peers	21		21	0.83
Collaborative/cooperative learning						
270	Johnson, Maruyama, Johnson, Nelson, & Skon (1981)	Cooperative learning	122		183	0.73
271	Rolhelser-Bennett (1987)	Cooperative learning	23	4,002	78	0.48
272	Hall (1988)	Cooperative learning	22	10,022	52	0.31
273	Stevens & Slavin (1991)	Cooperative learning	4		4	0.48
274	Spuler (1993)	Cooperative learning in math	19	6,137	19	0.54
275	Othman (1996)	Cooperative learning in math	39		39	0.27
276	Howard (1996)	Scripted cooperative learning	13		42	0.37
277	Suri (1997)	Cooperative learning in math	27		27	0.63
278	Bowen (2000)	Cooperative learning in high school chemistry	37	3,000	49	0.51
279	Neber, Finsterwald, & Urban (2001)	Cooperative learning with gifted	12		314	0.13
280	McMaster & Fuchs (2002)	Cooperative learning	15	864	49	0.30
281	Stoner (2004)	Cooperative learning	22	6,455	22	0.14
282	Romero (2009)	Cooperative learning	32		52	0.31

283	Williams (2009)	Collaborative learning	29	3,029	29	0.29
284	Igel (2010)	Cooperative learning	20	2,412	20	0.44
285	Nunnery, Chappell, & Arnold (2013)	Cooperative learning in math	15		15	0.16
286	Kyndt, Raes, Lismont, Timmers, Cascallar, & Dochy (2013)	Cooperative learning	43		51	0.54
Critical thinking techniques						
287	Abrami, Bernard, Borokhovski, Wade, Surkes, Tamim, & Zhang (2008)	Critical thinking interventions	117	20,698	161	0.34
Classroom discussion						
288	Murphy, Wilkinson, Soter, & Hennessey (2011)	Fostering classroom discussion	42		42	0.82
Problem solving teaching						
289	Marzano (2000)	Problem solving	343		343	0.54
290	Xin & Jitendra (1999)	Word problem solving in reading	14		653	0.89
291	Swanson (2001)	Programs to enhance problem solving	58		58	0.82
292	Marcucci (1980)	Problem solving in math	33		237	0.35
293	Curbello (1984)	Problem solving on science and math	68	10,629	343	0.54
294	Almeida & Denham (1984)	Interpersonal problem solving	18	2,398	18	0.72
295	Mellinger (1991)	Increasing cognitive flexibility	25		35	1.13
296	Hembree (1992)	Problem solving instructional methods	55		55	0.33

297	Tocanis, Ferguson-Hessler, & Broekkamp (2001)	Problem solving in science	22	2,208	31	0.59
298	Johnson & Johnson (2009)	Conflict based teaching	39		39	0.80
299	Zheng, Flynn & Swanson (2011)	Problem solving with math disabilities	8		8	0.78
Transfer						
Far transfer						
300	Rayner Bernard, & Osana (2013)	Far transfer in math	53		116	0.80
Seeing patterns to new situations						
301	Marzano (2000)	Experimental inquiry	6		6	1.14
Similarities and differences						
302	Marzano (2000)	Identifying similarities and differences	51		51	1.32

Appendix 4: All meta-synthesis effect sizes.

No.	Strategy	Model Category	No of Metas	ES
1.	Achieving approach	The Thrill	1	0.70
2.	Advance organisers	Success criteria	12	0.42
3.	Attitude to content	The Will	4	0.35
4.	Background music	Environment	1	-0.04
5.	Classroom discussion	Consolidating deep	1	0.82
6.	Collaborative cooperative learning	Consolidating deep	18	0.38
7.	Concept mapping	Success criteria	9	0.64
8.	Critical thinking techniques	Consolidating deep	1	0.34
9.	Deep approach	The Thrill	1	0.63
10.	Deep motivation	The Thrill	1	0.75
11.	Deliberate practice	Consolidating surface	3	0.77
12.	Effort	Consolidating surface	1	0.77
13.	Elaboration and organisation	Acquiring deep	1	0.75
14.	Elaborative interrogation	Acquiring deep	1	0.42
15.	Environmental structuring	Environment	2	0.41
16.	Evaluation and reflection	Consolidating deep	1	0.75
17.	Exercise	Environment	8	0.26
18.	Far transfer	Transfer	1	0.80
19.	Giving/receiving feedback	Consolidating surface	28	0.71
20.	Goal commitment	Success criteria	3	0.37
21.	Goal difficulty	Success criteria	7	0.57
22.	Goal intentions	Success criteria	2	0.68
23.	Goals (Mastery, performance, social)	The Thrill	11	0.48
24.	Help seeking	Consolidating surface	1	0.60
25.	Imagery	Acquiring surface	1	0.45
26.	Incremental v entity thinking	The Will	1	0.19

27.	Interleaved practice	Consolidating surface	1	0.21
28.	Mastery goals (general)	The Thrill	3	0.19
29.	Meta-cognitive strategies	Acquiring deep	5	0.61
30.	Mindfulness	The Will	3	0.29
31.	Mnemonics	Acquiring surface	4	0.76
32.	Note taking	Acquiring surface	7	0.50
33.	Organising	Acquiring surface	3	0.60
34.	Outlining & transforming	Acquiring surface	1	0.85
35.	Peer tutoring (becoming a teacher)	Consolidating deep	15	0.54
36.	Planning & Prediction	Success criteria	4	0.76
37.	Practice testing	Consolidating surface	10	0.44
38.	Prior achievement	The skill	9	0.77
39.	Problem-solving teaching	Consolidating deep	11	0.68
40.	Record keeping	Acquiring surface	2	0.54
41.	Reducing anxiety	The Will	8	0.45
42.	Rehearsal and memorisation	Consolidating surface	3	0.73
43.	Reviewing records	Consolidating surface	1	0.49
44.	Seeing patterns to new situations	Transfer	1	1.14
45.	Seeking help from peers	Consolidating deep	1	0.83
46.	Self consequences	Consolidating deep	1	0.70
47.	Self-concept	The Will	6	0.41
48.	Self-efficacy	The Will	5	0.90
49.	Self-explanation	Consolidating deep	1	0.50
50.	Self-monitoring	Consolidating deep	1	0.45
51.	Self-regulation	Acquiring deep	6	0.52
52.	Self-verbalisation & Self-questioning	Consolidating deep	4	0.64

53.	Self-verbalising steps in a problem	Consolidating deep	3	0.41
54.	Setting standards for self-judgement	Success criteria	1	0.62
55.	Similarities & Differences	Transfer	1	1.32
56.	Sleep	Environment	3	-0.05
57.	Social support	Environment	1	0.12
58.	Spaced vs massed practice	Consolidating surface	4	0.60
59.	Strategy monitoring	Acquiring deep	1	0.71
60.	Strategy to integrate with Prior knowledge	Acquiring surface	1	0.93
61.	Student control over learning	Environment	4	0.02
62.	Success criteria	Success criteria	1	1.13
63.	Summarisation	Acquiring surface	2	0.66
64.	Surface/performance approach	The Thrill	2	0.11
65.	Surface/performance motivation	The Thrill	3	-0.19
66.	Task value	The Will	1	0.46
67.	Teaching test taking	Consolidating surface	11	0.27
68.	Time management	Environment	2	0.40
69.	Time of day to study	Environment	3	0.12
70.	Time on task	Consolidating surface	8	0.54
71.	Underlining and highlighting	Acquiring surface	1	0.50
72.	Worked examples	Success criteria	2	0.37
73.	Working memory	The skill	4	0.68
74.	Working memory training	Acquiring surface	4	0.72

Appendix 5: The brain in the classroom

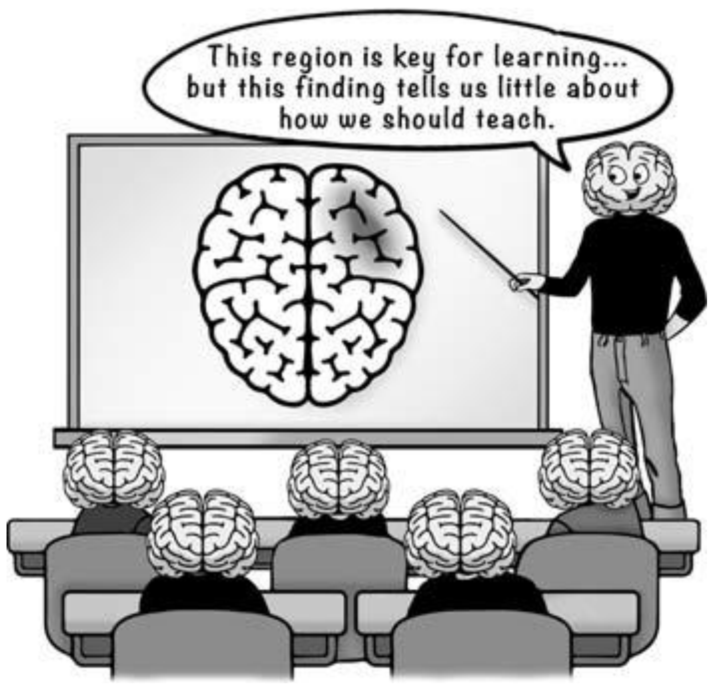
Donoghue, G.M. (2019). The brain in the classroom: The mindless appeal of neuroeducation..In R. Amir, & R.T. Thibault (Eds.), *Casting Light on the Dark Side of Brain Imaging* (pp. 37-40). London: Academic Press.

The brain in the classroom: The mindless appeal of neuroeducation

Gregory Donoghue

Since the 1990s scientists have promised a future where an increasingly sophisticated set of powerful brain-imaging tools would transform education as we know it. Nearly 30 years on, this future still hasn't arrived. In fact, neuroscience has yet to discover anything about education that good educators didn't already know. Consequently, educational practices remain largely unchanged since the emergence of educational neuroscience—or "neuroEd." Not only is there no evidence of neuroscience knowledge impacting educational practice or learning outcomes, there is a growing number of academics making the compelling argument that neuroscience alone can never prescribe how teachers should teach [1_4]. Why not? Because, simply put, brains don't learn. People do. To see why the claims of neuroEd warrant such skepticism, and how commonly used brain scans are being misapplied, we need to understand precisely what learning is—and what it isn't.

Neuroscience takes it for granted that the brain causes—or at least mediates—all thoughts, emotions, physiological responses, and external behavior [5]. Before the emergence of neuroscience, learning was traditionally considered a "more or less permanent change in behavior as a result of experience" [6,7]. More recently however, neuroscience conceives of learning as a change in the brain—more specifically, in the number, strength and type of connections between neurons [8,9]. Brain scanning technology provides an imperfect window into these changes—allowing us to observe changes in the neuronal structure and operation that coincide with behavioral, physiological, emotional, and cognitive events in the whole person.



Observed differences in the brains of people who think, behave, emote, or believe in distinct ways are therefore unremarkable. That is to say, if Anne has a certain level of cognitive or physical ability, thinks a particular way, or believes a certain thing, it should come as no surprise that we would observe differences in her brain compared to that of Marie who has a different level of ability, or thinks or believes in different ways. In the educational context, we should find it equally unremarkable that a person with different capacities, abilities, or intelligence should produce different brain scans. After all, it is the brain that causes, or at least mediates, all of these outputs. Changes in those outputs must therefore correspond with changes in the brain—some of which are measurable by our current suite of neuroimaging tools.

While the literature is replete with examples of these scans—for example, the "brain on music" [10], or the traumatized brain [11]—such studies essentially draw correlations between a known event in the whole person (e.g., a stressful emotion), and an observable event in the person's brain (e.g., the activation of the amygdala). This does little more than confirm the presupposition that the brain causes or mediates all behavior, emotions, physiology, and cognition. Such studies do not directly identify the cause(s) of the phenomenon, and provide no insight into how to facilitate it. The pictures are alluring—but they are silent on the question that most interests educators and learning scientists: how do we systematically enhance the desirable outcomes of human learning?

Despite the seductive appeal of neuroscience, especially publications that feature alluring images of the human brain [12], neuroscience is yet to provide any evidence that would of itself decisively shape the professional practices of educators. The absence of a meaningful link between neuroscience and education has been demonstrated on empirical grounds [4]. In a sweeping review of the major neuroEd literature (covering some 565 articles), we were unable to find a single neuroscientific study whose conclusion pointed toward adopting any particular educational practice over another [13]. This finding was despite many claims that such evidence may, in the future, do so.

Skeptics have also argued against neuroEd on theoretical grounds [2,3,14] highlighting the logical fallacy of using evidence from one level of complexity (say, cellular neuroscience) and drawing prescriptive conclusions about practices at a higher level of complexity (such as a complex sociocultural context found in a classroom). Human learning is essentially a highly complex neurological process, while teaching occurs in a complex web of interpersonal, social, and cultural factors. Education therefore can be seen as even more complex than neuroscience—as it includes neuroscience and sociocultural factors. Drawing inferences directly from brain scans to education ignores the properties that emerge in that more complex level—properties that simply cannot be conceived, let alone predicted or confirmed at the lower level.

Consider this representative quotation from an international neuroEd conference that accompanied a brain scan of the intraparietal sulcus (IPS): "the IPS is really important in learning math. It shows that if I can get my students to think in the way that their brains want them to, I can really get them learning." While it is true that the IPS is involved in mathematics learning, it is nonsensical to suggest that brains want anything. Wanting is an emergent phenomenon that simply does not exist at the neurological level. Brains do not want. People want. Brain scans may be compelling and may even improve our understanding of the neural correlates of learning, but to suggest that they can prescribe how we teach and learn is currently a logical fallacy, pure, and simple. Brain scans capture the neural correlates of learning—not the learning itself. The map is not the territory.

To see this fallacy illustrated, we need look no further than a recent, high-quality electroencephalogram study [15]. The authors produced a compelling brain-scan image of the "brain on growth mind-set" (where the person believes that effort can improve one's ability) compared to a "brain on fixed mind-set" (where the person believes that their ability is unchangeable).

The authors of this study validly concluded that there were measurable differences between the brain scans of people with a "growth mind-set" and those with a "fixed mind-set." More specifically, they stated that "people who think they can learn . . . have different brain reactions" [16] and that ". . . brain activity and cognitive control can be altered after reading a short article . . . regarding abilities" [17]. While these conclusions may be reasonable, they do not follow the evidence provided by the brain scans. The tendency to make overly broad conclusions on this type of evidence is very common in the neuroEd field. For example, one commercial enterprise used this study to declare that:

> . . . when we make a mistake, synapses fire. A synapse is an electrical signal that moves between parts of the brain when learning occurs. . . [this] is hugely important for math teachers and parents, as it tells us that making a mistake is a very good thing. Mistakes are not only opportunities for learning, as students

consider the mistakes, but also times when our brains grow [18].

Such a claim is a representative example of going way beyond the evidence while attempting to derive greater credibility from citing a neuroscientific source, complete with alluring brain-scan images [12]. Others claimed that this evidence “could help in training people to believe that they can work harder and learn more, by showing how their brain is reacting to mistakes” [16]. While this type of neurological evidence may generate hypotheses about what may happen in the classroom, it does not allow for such broad conclusions. In fact, the only evidence that can confirm best educational practices must be drawn from that educational context— not from a brain scan.

This is not to say that neuroscience has no role in educational research—it does, just not a prescriptive role. Instead, integrating neuroscience into education requires careful translation between the layers of complexity. A good example of how neuroscience can inform education has been demonstrated by the Science of Learning Research Centre [19]. Their PEN (Pyschology Education Neuroscience) principles comprise 12 core tenets in learning and teaching that are supported by evidence from each of the three layers of complexity most directly implicated in the learning.process. These are good examples of how prescriptive conclusions about what works in education are ultimately based on evidence from that educational context, while evidence from the two layers of lower complexity are drawn upon to confirm, explain, conceptualize, and generate hypotheses.

Until we more fully understand the neurological processes involved in learning, and we have developed nonpedagogical tools that can directly change brains in predictable and precise ways—such as electrical or magnetic stimulation techniques (see Chapter 18)—human learning will continue to be mediated behaviorally, experientially, and pedagogically. Until then, neuroscience cannot prescribe educational practices.

The human brain is one of the most complex structures in the universe, and.learning about it is a highly desirable pursuit. Educators may even find it worth their while to study the brain—if only to enable more informed decisions about brain-based products and programs. Brain scans will continue to inform, conceptualise, explain and theorize—but they will never prescribe how educators best teach, or how students best learn. Human learning will continue to be enhanced by educators who for thousands of years have been dedicated to their craft of teaching people, not brains.

Appendix 6:.Learning analytics and teaching: A conceptual framework for translation and application

Donoghue, G.M., Horvath, J.C., & Lodge, J.M. (2019). Translation, technology & teaching: A conceptual framework for translation and application. In J.M. Lodge, J.C. Horvath, & L. Corrin (Eds.), *Learning Analytics in the Classroom.* London: Routledge.

Abstract

At its essence, *human learning* is a complex neurological phenomenon that has traditionally been understood and measured through observable behaviour..More recently though, *Learning Analytics* (LA) has emerged to conceptualise and facilitate human learning by measuring *learning correlates*, including physiological metrics such as pupil dilation and perspiration rates. In this chapter, we show that these correlates of learning are distinct from actual learning (the map is not the territory), and warn of the risks and challenges of inferring truth from one discipline (LA) to another (education)..We demonstrate the importance of valid and logical *translation.*of LA evidence into education, and to this end we describe a conceptual framework and translation schema by which the benefits of LA can be validly translated, leading to the direct benefit of both educators and learners.

Introduction

At its essence, *human learning* is a complex neurological phenomenon. Ultimately, learning is instantiated by changes to the organisation of the human nervous system (Kandel, 2000; Gazzaniga 2004), corollaries of which include more or less permanent changes in behaviour (Mayer, 2003; Shuell, 1986). *Education*, on the other hand, is an even more complex sociocultural phenomenon that subsumes the biological, psychological, sociological and even physical sciences. In other words, learning involves both neurological processes, psychological phenomena, and sociocultural factors such as social interactions, cultural agents, relationships, and communication.

Learning Analytics (LA) is an emerging field that purports to support, enhance, facilitate, predict and measure human learning in educational settings. It achieves this largely by measuring *learning correlates* (an array of phenomena that exist or emerge when learning occurs), including, for example, reaction times, keyboard entries, mouse clicks, etc. More recently, this has been expanded through the use of multimodal learning analytics that also incorporate, for example, pupil dilation, pulse rate and sweat responses (Ochoa, 2017). It is important to note, however, that the *correlates* of learning are not the same thing as learning itself (see Gašević, Dawson & Siemens, 2015). For this reason, it is important to consider how the former can (and cannot) meaningfully be used to assess the latter. In addition, while collection of data from LA implementations often occurs in educational environments, making meaning of these data still requires translation in order to be valid. As with scientific or neuroscientific data, LA data also need be understood within the context in which it was produced in order to derive meaning both within and beyond that context. It is not sufficient to rely solely on algorithms to abstract this meaning.

Inferring truth from one discipline to another - in this case, from LA to education - is beset with problems of translation (see Lodge, Alhadad, Lewis & Gašević, 2017). These issues constrain and often invalidate applications of knowledge from one discipline to another; a topic that has previously been explored generally within science (Anderson, 2002; Horvath & Donoghue, 2016) and specifically within educational neuroscience (Donoghue & Horvath, 2016). The purpose of this chapter is to describe these structural translation problems and how best to address them. To that end, we propose a conceptual framework and translation schema by which LA can be meaningfully and validly translated into educational practice for the direct benefit of both educators and learners.

Human learning

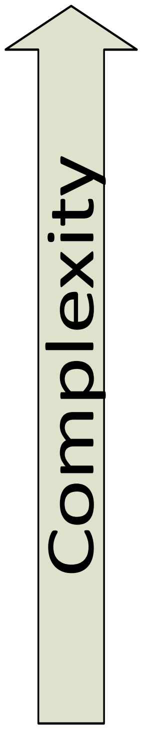
Human learning is purposeful. It is a complex biological phenomenon that is ultimately a physical process when viewed through a reductionist, materialist theoretical lens (see Palghat, Horvath & Lodge, 2017 for an overview). The capacity to learn from experience is a biological adaptation, favoured by natural selection as it enhances the biological fitness of the individual (Darwin, 1859; Geary, 2005). Geary, a pioneer in the field of Evolutionary Educational Psychology, applied Darwin's evolutionary theory to postulate that learning evolved because it enhanced the individual's ability to exert control over the physical world (by learning 'folk physics'), the animal world (by learning 'folk biology') and the human world (by learning 'folk psychology') (Geary, 2005). From this view, an increased probability of survival and reproduction are the ultimate desirable outcomes of human learning, and the 'purpose' for which it evolved.

Consequently, learning is instantiated within neurology: as the individual experiences events in the internal (physiological) or external (environmental) worlds, s/he receives information through a range of internal and external sensory organs. These organs are tissues that consist largely of the sensory components (dendrites) of neurons – for example the mammalian retina consists of a tissue of retinal neurons, the dendrites of which flatten out along the back of the eye to receive light. The light stimulus is detected in the sense organ, and transduced into electrical signals that are then transmitted along neuronal extensions (axons), encoded, and eventually stored *as information* in and between the approximately 80 billion neurons in the brain (Eichenbaum, 2011). Learning occurs when the information stored within these neural networks is changed in some way, typically by altering either the number or strength of neuronal connections. These changes, in turn, underpin more-or-less permanent changes to behavioural, cognitive, emotional and physiological responses (Okano et al., 2000).

Nonetheless, human learning does not happen in neurological isolation: it is heavily embedded within other biological systems such as the physical organs, physiological and endocrinal systems and emotional processes that exist across the entire individual person (not simply within the brain). Further, learning as engendered by education is heavily embedded within society, culture and the physical (non-biological) environment (Bronfenbrenner, 1977; Bandura, 2001). When attempting to infer what specific types of data might contribute to understanding learning across this complex, systemic milieu, researchers and educators alike must carefully consider what these data actually indicate about learning processes and outcomes.

Donoghue & Horvath (2016) propose a conceptual framework that can be used to organize these varied levels of data. It is based on a multi-layered, abstraction model for computer networks known as the Open Systems International (OSI) model (International Organization for Standardization, 1994). This framework divides learning into five discrete layers according to the level of biological complexity. At the lowest level (Layer I), learning is conceived as physical - interactions between non-living atoms that can occur, for example, in computer networks, or within complex proteins. Most discussion of human learning however begins with the neuron, which is a specialised living cell. This is represented in Layer II, where cellular learning is conceived as a phenomenon of interactions in and between neurons. When many neurons combine, a tissue emerges (neuronal tissue), and when several tissues combine, an organ (the brain) emerges. This is represented in Layer III. When many organs combine, an organism emerges (a holistic person) - represented in Layer IV. Finally Layer V represents the combination of many people - the emergence of a population, society or culture. This can be depicted as follows:

matter → cells → organs → organisms → populations



Layer No.	Layer Name	Components
V	**Population**	Organised collections or *populations* of individuals into social, cultural groups.
IV	**Individual**	Organised collections of organs into individual persons or *organisms*
III	**Organ**	Organised collections of cells and cellular issues into *organs*
II	**Cellular**	Organised collections of atoms and molecules into *cells.*
I	**Physical**	Physical matter - atoms and molecules, including biochemicals.

Table 2.1: Layers of Complexity in Human Learning

While *learning* at the cellular and organ layers is a complex neurological phenomenon, *human learning* is an even more complex sociocultural phenomenon. It is underpinned by neuronal learning but also involves other, non-neuronal features that exist at the Individual layer such as personality, emotions, internal physiology and behavioural responses. Furthermore, education is more complex again as it includes neuronal and human learning but also involves factors from the Population layer such as society, culture, and interpersonal communication. In this schema, education is conceptualised as the result of interactive social, cultural, psychological, biological, cellular and physical phenomena. Just as population health is more than the biological basis of disease, education is more than the neurological or psychological bases of human learning.

Learning Analytics

Learning analytics (LA) is a new and exciting field that promises to inform education and consequently facilitate human learning. By applying a raft of computational, statistical and other tools to learning environments, LA is able to provide data about learner behaviour that is correlated – sometimes even causally correlated – with successful learning. Within this larger range of possible points of analysis of human learning, LA can be situated at specific points along the continuum from neuron to society. Initial progress in the field tended to focus on log file or interaction data generated as learners interacted with digital learning environments (e.g. Judd & Kennedy, 2011). As most of these data are measures of the individual learner's externally detectable behaviour (Lodge & Lewis, 2012), they generally fell into the Individual Layer IV in the framework presented above. Recent advances, however, make it possible to generate data from all five layers.

In the past, some proponents were optimistic that LA could do away entirely with learning theories (see Wise & Shaffer, 2015). The field has since evolved to become an important 'source of information for educators to make complex decisions' (Merceron, Blikstein & Siemens, 2015), and to capture data to accurately reflect 'the complexity of the learning process' (Siemens, 2013).

There are ongoing debates about what can actually be inferred from both the data generated as students go about learning and from the predictive models that are increasingly being used to organise these data (e.g. Kovanovic, Gašević, Dawson, Joksimovic & Baker, 2016). As argued by Lodge et al. (2017), there are some clear parallels between the issues that have occurred in educational neuroscience and some of these ongoing debates in learning analytics. In both cases, large volumes of data are being produced while researchers, statisticians, teachers and others seek to infer learning from these datasets. The availability of rich data about how learning occurs in the brain has led to an explosion in efforts to understand the neural and cerebral correlates of learning. While this endeavour has provided great insights into learning at a biological level, extracting meaning from these data for educational practice has been fraught. This is perhaps best exemplified by the rise and persistence of 'neuromyths' in education (Bowers, 2016; Geake, 2008; Decker et al, 2012; Pasquinelli, 2012): misconceptions that are mostly based on an invalid translation of neuroscience into an educational context. It is worth devoting some effort to consider whether big data and LA are prone to similar logical errors.

The rise of neuromyths points to the seductive allure of neuroscience explanations (see Weisberg et al, 2008). To make a persuasive claim about a new educational innovation, one need only to add a picture of a brain to convince many of its efficacy. In a similar vein, developments in LA and data science applied to education also bring with them a seductive allure, as has been evident in many innovations in educational technology (see Lodge & Horvath, 2017). To make a persuasive claim about a new LA-based educational innovation, one need only mention Machine Learning and AI to convince many of its efficacy. 'Data is the new oil' as the saying goes. In both instances, great care needs to be taken in what we can infer about learning through the data being produced.

In both educational neuroscience and LA, the aim is to try to understand learning through a specific data-driven lens. In neuroscience, that lens is biological, in LA, that lens is behavioural (though obviously other forms of data are also implicated here), and often the behaviour/s of interest are sub-conscious. The underpinning issue in both fields is the same: education is a complex, multidimensional, contextual and social phenomenon, and attempting to understand how it occurs purely through a biological or behavioural lens is risky. Great care must be taken not to infer beyond what the data can reliably and validly tell us. Inferring directly from a brain imaging study to what happens in a whole person is problematic, as is inferring from purely behavioural data into a sociocultural context such as a classroom. Drawing on Donoghue & Horvath (2016), we instead propose a process of translation that is more systematic and takes into account the various levels of abstraction involved.

An abstracted framework for the learning sciences

Building on the progression of complexity outlined earlier in this chapter, we propose an Abstracted Layered Framework (see Table 2: Donoghue & Horvath, 2016; Horvath & Donoghue, 2016; Lodge et al., 2017) to situate the predominant disciplines that comprise the Science of Learning. We further propose that LA (currently and largely) resides in the Organism or Individual layer, one layer of complexity below the sociocultural layer in which *education* resides.

Table 2. Proposed layered abstraction framework for the learning sciences (From Donoghue & Horvath 2016)

Layer	**Developmental phase**	**Layer name**	**Relevant discipline**	**Function**
V	Populations	Sociocultural	Education, social sciences	Individuals interact with other organisms and systems in ecological, sociocultural contexts in which information is processed and transmitted. This communication leads to group wide behavioural patterns, cultural norms and larger societal value sets (e.g. what should be included in curriculum?)
V	Organisms	Individual	Cognitive & behavioural psychology	The complete complement of biological, psychological and emotional systems embodied in an individual person. Communication between individuals generates larger sets of behaviour which are typically measurable and conscious

Table 2. Proposed layered abstraction framework for the learning sciences (From Donoghue & Horvath 2016)

Layer	**Developmental phase**	**Layer name**	**Relevant discipline**	**Function**
III	Organs	Cerebral	Systems, cognitive and behavioural neurosciences	Groups of neurons form connections with other neurons and non-neuronal cells to form larger networks. Patterns of network activity and excitability allow for the transmission and processing of information within and between specific organs in the body. This communication leads to specialised, occasionally unmeasurable and largely subconscious proto-behavioural patterns
I	Cells	Cellular	Biology/pure neuroscience	Unspecialised cells can individually store, encode, process and transmit information by use of proto-neurotransmitters which float freely in the cytoplasm. Specialised neurons capable of storing, processing and transmitting information
I	Matter	Physical	Physics	Information obtained from the external environment can be encoded, stored in, and occasionally transmitted between atoms, particles and complex molecules. Examples include machine learning (supervised and unsupervised) in computing devices

Can scientific data and evidence drawn from one field - in this case empirical LA data drawn from individual student behaviour in technological environments - be extrapolated into conclusions in another more complex field – in this case a sociocultural learning environment? We argue that the answer is largely ‘no’, but it can become ‘yes’ if those data are validly and logically translated between layers of the Abstracted framework. To this end, we propose four specific forms of such translation.

Forms of translation

In Horvath & Donoghue (2016) four different forms of translation are proposed and described: prescriptive, conceptual, functional, and diagnostic.

Prescriptive translation aims to directly inform an educator or learner what specific behaviours or actions they need to adopt in order to facilitate learning.

Conceptual translation allows educators and learners to form a high-level theoretical explanation of specific learning interventions and why each does or does not work. This type of translation is silent on what a learner or teacher should do, making it distinguishable from prescriptive translation.

Functional translation enables educators and learners to be informed about the constraints to learning imposed by physical, mental and physiological abnormalities. As a trivial example, damage to a learner’s auditory cortex leading to deafness would constrain the means by which that student could effectively learn. While knowledge of this functional constraint may inform the teacher to use non-auditory teaching methods for example, it would not inform the learner or teacher what teaching and/or learning practices to use in order to facilitate learning, making it distinguishable from prescriptive translation.

Finally, diagnostic translation allows for the diagnosis of learning behaviours and disabilities without relying on the usual measures of self-report, external testing, or teacher observation. This translation process usually involves the following steps: identify those students who exhibit a particular learning issue (desirable or undesirable); generate a secondary measure at the biological or sub-conscious behavioural level (such as a functional MRI pattern, a clickstream analysis, or a pupil dilation measure); draw a statistical correlation between the two; and, when the secondary measure is observed, conclude that the original learning issue must therefore exist. Many LA interventions fall into this category. For example, attempting to trace student behaviour in enterprise systems in order to determine whether they are ‘at risk’ is a form of diagnostic translation. Importantly, the effective diagnosis of a behaviour does not inform the learner or teacher what to do in order to amend or support that behaviour, making it distinguishable from prescriptive translation.

Each of the above represents a valid form of translation, except prescriptive. As outlined below, prescriptive translation (which is the most sought after and touted form of translation) is a chimera that can negatively impact the effective translation of LA data into the classroom.

Table 2.2 Forms of Valid Translation

Type	*Description*
Prescriptive	*Describes specific teaching and learning practices that should be adopted on the basis of research. Cannot validly cross layer boundaries*
Conceptual	Information from one layer is used to conceptualise, theorise or broadly understand a specific topic or behavior..Can validly cross layer boundaries.
Functional	Describes constraints that are imposed on learning, teaching and education by underlying physical, neurological, physiological conditions. Can validly cross layer boundaries.
Diagnostic	Identifies learning-related conditions using neurological, physical or psychological diagnoses. Can validly cross layer boundaries.

Ultimately the true test of any learning intervention, method of analysis, pedagogical practice or educational system – LA included - is whether it is ‘fit for purpose’ (Mor, Ferguson & Wasson, 2015); that is, does it impact educational practice? In the case of LA, the true test of the validity of the metrics collected in LA research is whether they facilitate – that is, are causatively correlated with - desirable learning outcomes in educational settings such as classrooms. Simply because an intervention leads to, for example, a set of physiological or behavioural reactions (such as activation of a particular area of the brain or keystroke behaviour) that are *correlated* with learning, it does not logically follow that the learning will occur. This is consistent with the argument made by Gašević, Dawson, Rogers and Gasevic, (2016) that there is no single way of making meaning of learning analytics.

It is valid to say that under *these* conditions, at *this* time, with *these* students, *this measure* was strongly correlated with *this* particular learning outcome. However, it is not valid to say that that “*this* measure (made in the Organ or Individual layer) shows that teachers should teach in *this* way (Population layer)”. Though this type of statement may make a good hypothesis, it is not proof one way or the other. This is one reason why Prescriptive translation does not validly cross layer boundaries. The ultimate - and only valid - test of an educational phenomenon is its effectiveness when studied in the educational (Population) layer.

The metrics used in LA (biosensors, clickstreams, eye trackers, and the like), derived as they are from examining the individual learner, inform the facilitation of learning. That is, they are *proxies* of learning – not direct measures of learning itself as it occurs in a sociocultural (educational) context, despite much of the data being collected in this context. While educators are concerned with facilitating learning in a complex sociocultural context, LA researchers operate with behavioural, psychological and physiological correlates of learning in the individual person. To conclude that what works in the individual context will invariably work in a broader sociocultural context is logically fallacious and an example of invalid translation.

Prescriptive translation

As might be expected, the primary form of translation most desired and expected by practising educators is prescriptive (Pickering & Howard-Jones, 2007; Hook & Farah, 2013). Arguably, though, this is the most problematic as it requires drawing questionable and logically flawed conclusions about what teachers or students ought to do in the classroom from evidence that was collected in totally different layer. It is worth noting that behavioural data collected in a complex classroom context or digital learning environment is still behavioural data. We argue that, because that it is invalid to dictate behaviours across layers, prescriptive translation can only occur in the layer in which the research is undertaken. This is so for two reasons. First, just as a map can never be the territory, an abstracted metric of a construct can never be the construct itself. What a learner does on a laptop or website is a *correlate* of learning, but is not learning itself. That is to say, a learner's practice of mouse clicks at the right time, reviewing videos and typing in responses on forums *are not* the students learning *per se* – they are phenomena that are associated with, or occur at the same time as learning (see also, Lodge & Lewis, 2012). When a student is learning, these correlates are apparent; and in some cases (when that correlation is causative), performing these correlates can improve learning. In neither case however, are these practices the learning itself.

Second, evidence collected at one layer can only be concerned with the phenomena that exist in that layer. It is invalid to draw conclusions about phenomena that *emerge* at higher layers using evidence gathered at lower layers, where those emergent phenomena simply do not exist (for a detailed discussion, see: Horvath & Donoghue, 2016). For example, the concepts of motivation, desire, and boredom do not exist, and therefore have no meaning, at the cellular level. As such, attempting to draw a prescriptive conclusion about these concepts using the language of biochemicals makes little-to-no sense (this is why we typically see massive overlap between neurotransmitters and larger behavioural functions – sometimes with contradicting behaviours apparently being mediated by identical neurological phenomena).

Accordingly, we argue that LA research cannot *prescribe* practices in the Population layer. Such research can be conceptually, functionally or diagnostically translated, but not prescriptively. This is perhaps one of the greatest issues in implementing LA. The use of big data, algorithms and predictive models allude to a level of precision that is simply not possible. The level of analysis and application are incommensurate, just as they are in educational neuroscience. At best, LA research can generate testable hypotheses regarding potential interventions that may enhance learning at the sociocultural layer. The ultimate test of any educationally relevant hypothesis, however, is testing in real-world educational contexts that incorporate all the variables, preconditions and emergent phenomena that exist only in that layer.

In the classroom

The following process is proposed for the valid translation of learning analytic findings into education. First, recognise that educators belong to the profession with the best knowledge about what works in the complex sociocultural context that is education. Other disciplines, including LA, neuroscience, cognitive psychology, economics, and evolutionary biology can *inform* that professional practice, but ultimately, if the objective of education is learning in a sociocultural context, then measurement of human learning in that context is the ultimate measure of the effectiveness of any proposed intervention. This means that educators are not tools in the researcher's belt, they are arguably the most important agent in human learning as they hold the ultimate knowledge that will make (or break) any behavioural or neuroscientific hypothesis. As other chapters in this volume have highlighted, learning design is critical for making sense of these data for practice. Central to the design process is the teacher, who understands the context and is best place to decide how to act on the basis of the data.

Second, identify the layer in which research, interventions or measurements are being conducted. Largely, this is going to be from the Organ or Individual layers – as the metrics gathered by LAs is predominantly from the students' physiological responses or observable behaviour: what clicks, mouse moves, page views they conduct, what their body is doing visibly (behaviour) and physiologically (biometrics). This will ensure others (especially educators) quickly recognize what forms of translation are being undertaken and, by extension, what work may be required to advance that translation into the classroom.

Third, identify the layer into which findings are to be extrapolated. If extrapolation is reaching beyond layer boundaries, then the limitations of translation must be respected, lest *non sequiturs* are the result, leading to incommensurate (and ultimately meaningless) conclusions. Fourth, assumptions underpinning these findings must be logically explicated. For instance, if data are correlational, then resultant conclusions must be provisional and further explored in different layers.

While LA traditionally focused on the interpretation and extrapolation of data gleaned from learners' externally visible behaviours, more recent work is gleaning data from sources that are less subject to the learners' conscious control (so-called biometrics such as pupil dilation, saccadic eye movements, galvanic skin response, heart rate, blood pressure, and micro facial expressions). The principles and applications of valid translation apply equally to these new forms of data.

Conclusion

As described in the introduction, human learning is an evolved and purposeful phenomenon. It leads to a broad range of desirable outcomes that educators and learning scientists seek to facilitate. These outcomes can impact individuals, communities and even the environment, but are only deemed desirable when individuals and communities, in accordance with their own values, decide they are so. Such decisions are outside the realm of empirical science – it can quantify the best means of achieving a particular value, but is silent on the question of what values should, or should not, be pursued. LA data, in contrast, are drawn from robust, peer-reviewed empirical science, and can therefore be used to identify the most effective ways of achieving those desirable learning outcomes. We have warned that 'a map is not the territory', and that these data describe *correlates* of learning, but do not constitute learning itself. Further, we have identified the dangers of directly extrapolating those data directly into educational practice, and proposed a conceptual framework and translation schema for LA. The application of these concepts is one viable way in which LA research can be validly and meaningfully translated into the classroom. In doing so, the errors of previous neuroeducational interventions can hopefully be avoided.

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Appendix 7:.A model of learning

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A model of learning: Optimizing the effectiveness of learning strategies

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Introduction

There is a current focus on the development and measurement of twenty-first century skills. This search has been conducted for millennia – at least since Socrates, Plato, and Aristotle. We still use Socratic questioning, probing questions, seeking evidence, closely examining reasoning and assumptions, tracing implications, searching for unintended consequences, and appealing to logical consistency. In these days of 'false news' Socrates would have been exemplary in carefully distinguishing those beliefs that are reasonable and logical from those that lack evidence and rational foundation to warrant our belief. Plato wanted his students to distinguish between what 'appears to be' from what they 'really are' beneath the surface, to come out of the cave, and be responsive to objections. Such critical thinking, resilience, and problem solving that many are claiming to be the defining attributes of the 21st century should instead be called 5th century BC skills.

Similarly, there are many schools running critical, creative and learning strategy classes; countries that require collaborative problem solving courses to be built into their curricula, and numerous web sites claiming to “train the brain”. There are many myths about the implications of neuroscience into learning, and in many cases these are akin to sowing a thousand weeds. It is an empirical question whether learning strategies can be effectively taught separately from content, and which of these strategies is more effective in transforming a student’s learning and achievement outcomes. The current industry of apps, web sites, interactive games often ignore the eons of research on learning, as illustrated by the chapters in this book.

It is also our observation that the teaching of “learning” has diminished to near extinction in many teacher education programs. At best, there are passing references to Vygotsky’s zone of proximal development; the use of constructivism (but this is normally presented as method of teaching rather than a theory of learning; (see Bereiter & Scardamalia, 2014); the development of learning progressions (in which adults generally prescribe a scope and sequence to be pursued, despite this often being independent of how students actually progress); and an over dominance on how to teach content and less focus on the methods of learning this content. When we ask teachers to name at least two theories of learning, the most common default response is Piaget or constructivism. Worse, those methods known to be failures are often referenced: learning styles, training the brain as a muscle, giving students control over learning (rather than teaching them how to have this control, and understanding what “control” means). We reviewed over 1000 hours of transcripts of teaching lessons for example to illustrate how some teachers teach students how to learn but, other than some questioning the student about how they go to that answer, we failed to find any.

In our workshops we ask teachers and their students "how do you think" and most struggle. The point is that we do not have a rich language of thinking despite the C21 claims, and despite the rich knowledge and theories of learning. Often, the comment is "I learn this way" whereas, as will be seen in this chapter, the attribute of successful learners is their flexibility to apply the optimal strategies at the optimal time. Other defining attributes include adaptiveness - knowing multiple ways to learn; knowing when to use a strategy and when to not use this strategy; knowing what to do when we do not know what do. A return to understanding "learning" is needed, and the recent development of the "Science of Learning" and the excitement about relating neuroscience, cognitive psychology, and education promises a worthwhile future.

Knowing what learning strategies do and do not work is the science of learning; knowing when, where and in what combination to use them for any individual learner, is the art of teaching.

There is indeed a rich literature in learning strategies and our search located over 400; some were relabeled versions of others, some were minor modifications of others. Indeed creating taxonomies have been a valuable contribution by various researchers. Boekaerts (1997), for example, argued for three types of learning strategies: (1) cognitive strategies such as elaboration, to deepen the understanding of the domain studied; (2) metacognitive strategies such as planning, to regulate the learning process; and (3) motivational strategies such as self-efficacy, to motivate oneself to engage in learning. Dignath, Buettner and Langfeldt (2008) added a fourth category—management strategies such as finding, navigating, and evaluating resources. Our aim was to locate evidence on the effectiveness of these strategies, to evaluate which moderators were most critical, and to make relative comparisons of the learning strategies. Perhaps there are a top ten learning strategies (see Dunlosky et al., 2013), but identifying the moderators and mediators as important, in our view, as identifying the strategies themselves: consequently, this was an underlying theme in our search.

There was the usual iterative consideration of the empirical and theoretical tensions, and in the process of our meta-synthesis we built a model that helped serve as the coat hanger for understanding the empirical claims. Like all models, it provides a set of conjectures, it aims to provide explanatory power, it helps explain the empirical findings, and to generate future research questions. The model contains a proposed set of explanations, relations and causal directions, all of which are subject to testing, the evaluation of the degree of corroboration, the investigation of implications and conjectures, and ultimately to the usual rigors of tests of empirical and logical falsifiability. As Popper (1968, p. 280) claimed: “Bold ideas, unjustified anticipations, and speculative thought, are our only means for interpreting nature … and we must hazard them to win our prize. Those among us who are unwilling to expose their ideas to the hazard of refutation do not take part in the scientific game”. Hence to our model.

A model of learning

The model comprises the following three components: learner inputs, learning agents, and learning outcomes, and these are depicted in Figure 1. The student arrives at a given learning experience with a pre-existing set of personal qualities, abilities, knowledge and histories, all of which may impact their subsequent learning. We call these inputs, and categorize them into either Skill (knowledge and ability), Will (the student's dispositions that affect learning) and Thrill (motivations, emotions and enjoyment of learning). These three categories also describe the Outcomes of the learning process, and mediating Inputs and Outcomes are the Learning Agents – those phenomena that facilitate learning, be they direct, pedagogical, intentional or otherwise: these include Success Criteria, the Environment, and Learning Strategies. In our model, we propose that these learning agents can impact learning at either a factual-content (Surface) level, an integrated and relational (Deep) level, and when learning is extended to new situations

(Transfer). Finally, learning at each of these levels can be distinguished further, depending on whether the student is first encountering or acquiring into new learning, and whether the student is consolidating the learning at the Surface and Deep stages.

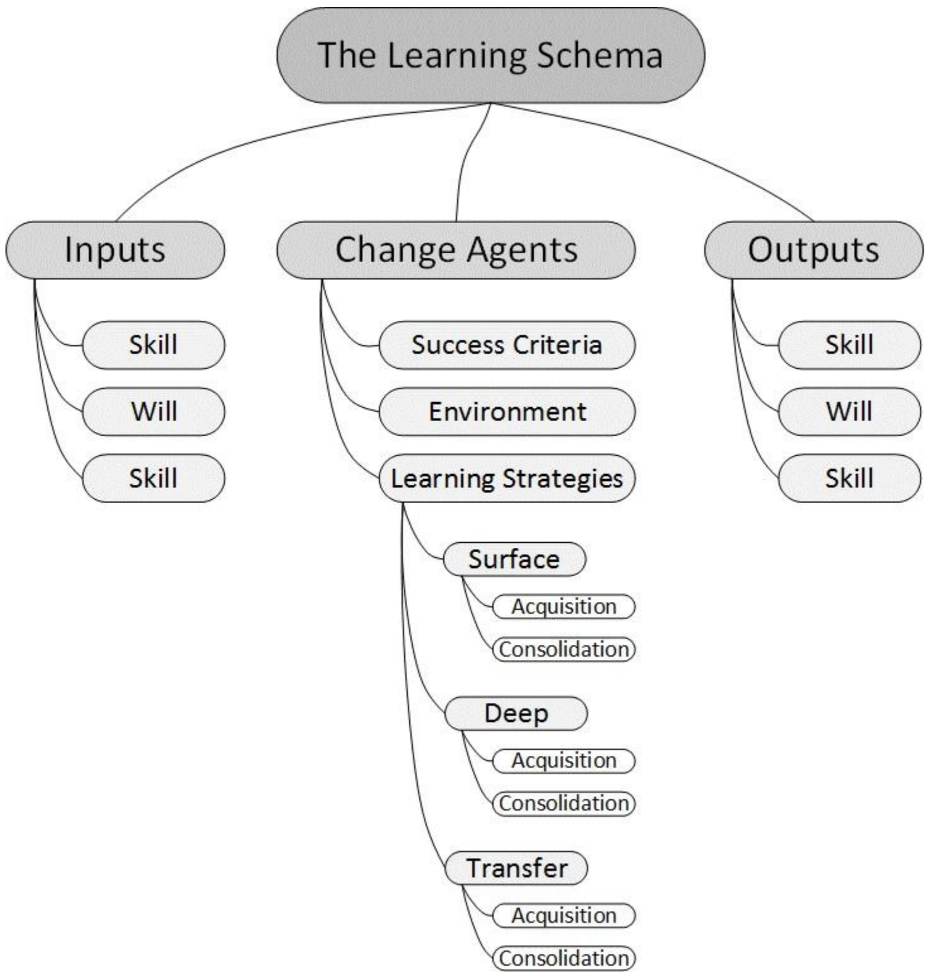

Figure 1: The learning schema

The model proposes that various learning strategies are differentially effective depending on the students prior knowledge, disposition to learn, motivation to learn (which includes) the degree to which the students are aware of the criteria of success. The strategies are differentially effective depending on whether the learning relates to ideas and surface level knowledge, to relations and deeper understanding, and to the strategies relating to transferring their knowing and understanding to near and far transfer tasks. Finally, within the surface and deeper phases, the strategies are differentially effecting depending on whether the student is acquiring or consolidating their understanding.Evidence related to this model is provided via a meta-synthesis based on 18,956 studies from 228 meta-analyses. Only 125 of these meta-analyses reported sample size (N = 11,006,839), but if the average (excluding the outlier 7 million from one meta-analysis) is used for the missing sample sizes, the best estimate of sample size is between 13 and 20 million students. The average effect is 0.53 but there is considerable variance. The details of all phases of the model and results are presented in Hattie and Donoghue (2016; see also Donoghue & Hattie, under review).

Input and outcomes

Figure 2 shows the proposed model, including the types and phases of learning described above, depicted with a proposed sequence. Notwithstanding, it should be noted that this sequence is not unidirectional, as in reality learning will occur iteratively, non-linearly, and with much overlap between the phases.

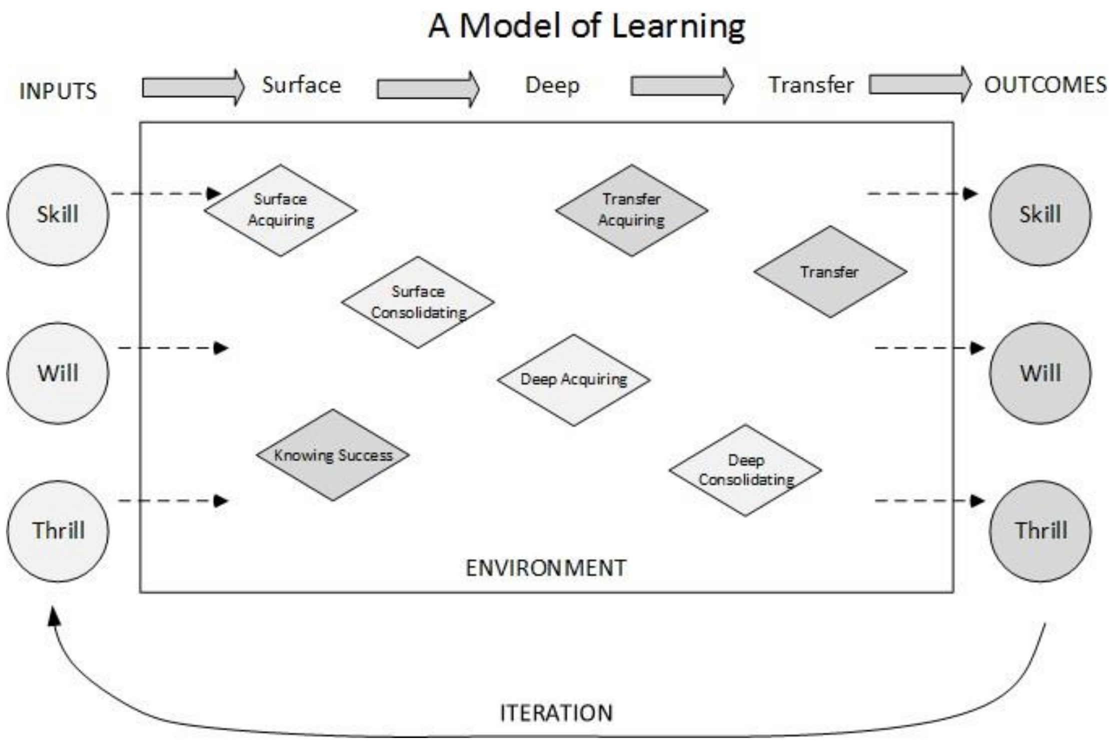

Figure 2: A model of learning

The model starts with three major sources of inputs: the skill, the will and the thrill. The 'skill' is the student's prior or subsequent achievement, the 'will' relates to the student's various dispositions towards learning, and the 'thrill' refers to the motivations held by the student. In our model, these inputs are also the major outcomes of learning. That is, developing outcomes in achievement (skill) is as valuable as enhancing the dispositions towards learning (will) and as valuable as inviting students to reinvest more into their mastery of learning (thrill or motivations). Each of these inputs, and more obviously the outputs, are desirable learning outcomes

– in and of themselves – and are open to being influenced by teaching, both directly and indirectly, both intentionally and unintentionally.

The skill

The first component describes the prior achievement the student brings to the learning task (d=.77). Illeris (2007) claimed that “the outcome of the individual acquisition process is always dependent on what has already been acquired” (p. 1). Other influences related to the skills students bring to learning include their working memory, beliefs, encouragement and expectations from the student’s cultural background and home.

The will

The will, in contrast, are dispositions, habits of mind or tendencies to respond to situations in certain ways, and here is where many of the so-called 21st century skills can be placed. The popular dispositions of grit, mindfulness and growth versus fixed mindsets have low effects (d=.19). This shows how difficult it is to change to growth mindsets, which should not be surprising as many students work in a world of schools dominated by fixed notions—high achievement, ability groups, and peer comparison. Moreover, Dweck (2012) has been careful to note that having a growth mindset is optimal in situations of adversity, helplessness, error, and where failure is a risk. She has also repeatedly ntoed that there is not necessarily a generic state of “growth mindset” but the more specific to situations. Indeed, a growth mindset can be a fixed notion! Schwartz, Cheng, Salehi and Wieman (2016) also noted that these dispositions may be worthwhile for students most at risk for poor academic achievement and Yaeger et al's (2016) intervention only had impact on students in the bottom fifth of achievement. Crede et al. (2016) showed that the core concept in "grit," often considered a core of growth mindset is conscientiousness, and it is well documented how hard it is to change this personality disposition.

The thrill

There can be a thrill in learning but for many students, learning in some domains can be dull, uninviting and boring. There is a huge literature.on.various.motivational aspects of learning, and a smaller literature on how the more effective motivational aspects can be taught. A typical demarcation is between mastery and performance orientations. Mastery goals are seen as being associated with intellectual development, the acquisition of knowledge and new skills, investment of greater effort, and higher-order cognitive strategies and learning outcomes. Performance goals, on the other hand, have a competitive focus: outperforming others or completing tasks to please others. The correlations of mastery and performance goals with achievement, however, are not as high as many have claimed (Carpenter, 2007; Hulleman *et al.*, 2010).

Most modern theories of motivation assume a student needs to be "pulled or pushed" such as *wanting* to master, or *competing* with one's peers. An alternative and more defensible basis of motivation is the notion of *striving*: recognizing that life does not stand still, and the learner will "moving forward" in any event, the important motivation question becomes "will I do *this* or *that*" (Hoddis, Hattie, & Hoddis, 2016; Peters, 1958). These striving theories of motivation have a higher chance of explaining why students engage in one activity or an alternative (e.g., on or off task). Higgins

(2011), for example, argued that we strive for value, control and truth effectiveness and we do this through promotion or preventive striving; that is we seek evidence for confirming current beliefs in ourselves (“I am a competent or a failure student”) or seek evidence disconfirming their current beliefs to thence have self-evidence of the truth effectiveness of their beliefs about themselves as learners (I worked hard and passed this assignment so I am an OK student; see also Swann, 2011). In many senses this is akin to the distinction Popper (1968) makes between confirmation and disconfirmation band helps explain why we continue to do one thing rather than another.

To enact these strivings, Biggs (1993) combined the motivation strivings (why the student wants to study a task) and their related strategies (how the student approaches the task). He outlined three common approaches to learning: deep, surface and achieving. When students are taking a deep strategy, they aim to develop understanding and make sense of what they are learning, create meaning and make ideas their own. This means they focus on the meaning of what they are learning, aim to develop their own understanding, relate ideas together and make connections with previous experiences, ask themselves questions about what they are learning, discuss their ideas with others and compare different perspectives. When students are taking a surface strategy, they aim to reproduce information and learn the facts and ideas—with little recourse to seeing relations or connections between those facts and ideas. When students are using an achieving strategy, they use a ‘minimax’ notion—minimum amount of effort for maximum return in terms of passing tests, complying with instructions, and operating strategically to meet a desired grade. It is this achieving strategy that seems most related to school outcomes.

The Learning Agents

Success Criteria

As important as the exploration of learning strategies themselves is the study of the mediators of those strategies. A major mediator is the degree to which the learner is aware of the criteria of success of the learning, along with the value they place on attaining these success criteria. Some students will engage in most activities regardless; indeed teachers value such compliant students. But many, particularly as they move to senior elementary schools start to question the purpose, authenticity, and value of investing energies into attaining undesirable or unknown outcomes. The time for compliance is over; students value control, knowing, and understanding more than they value externally defined success criteria. Students’ behaviors become more goal- directed when they are aware of what it means to be successful before undertaking the task. Students who can articulate or are taught these success criteria are more likely to be strategic in their choice of learning strategies, more likely to enjoy the thrill of success in learning, and more likely to reinvest in attaining the criteria of success.

The evidence from the meta-synthesis is that the key component of *Thrill* is having the cognitive flexibility to know when to be deep and surface (d=.70), provided the student does have deep strategies (d=.63) and motivations (d=.75)..Having mastery (d=.19) or performance (d=.11) goals have little import. The thrill is increased when students are exposed or invited to co-construct success criteria early in a sequence of instruction (d=1.13). This could be accomplished through teaching students how to develop concept maps (d=.62), develop standards for self-judgment of their work relative to the success criteria (d=.62), and using the Goldilocks principle of "not too hard, not too boring (d=.57; see Lomas, et al., 2016).

Environment

Underlying all components in the model is the environment in which the student is studying. Many books and internet sites on study skills claim that it is important to attend to various features of the environment such as a quiet room, no music or television, high levels of social support, giving students control over their learning, allowing students to study at preferred times of the day and ensuring sufficient sleep and exercise.

Despite the inordinate attention, particularly from parents, on structuring the environment as a precondition for effective study, such effects are generally relatively small. It seems to make no difference whether there is background music (d=-.04), whether students control over learning (d=.02), the time of day to study (d=.12), the degree of social support (d=.12), or the use of exercise (d=.26). Given that most students receive sufficient sleep and exercise, it is perhaps not surprising that these are low effects – of course, extreme sleep or food deprivation are likely to have marked effects on learning. Finally, it is important to note that these data are silent on the question of whether things like music, exercise and autonomy, are desirable learning phenomena in their own right.

The Learning Strategies

The three phases of learning: Surface, deep and transfer

The model highlights the importance of both surface and deep learning and does not privilege one over the other, but rather insists that both are critical. Although the model does seem to imply an order, it must be noted that these are fuzzy distinctions (surface and deep learning can be accomplished simultaneously), but it is useful to separate them to identify the most effective learning strategies. More often than not, a student must have sufficient surface knowledge before moving to deep learning and then to the transfer of these understandings.As Entwistle (1976) noted, ‘The verb ‘to learn’ takes the accusative’; that is, it only makes sense to analyze learning in relation to the subject or content area and the particular piece of work towards which the learning is directed, and also the context within which the learning takes place. The key debate, therefore, is whether the learning is directed content that is meaningful to the student, as this will directly affect student dispositions, in particular a student's motivation to learn and willingness to reinvest in their learning.

Acquiring surface learning

Surface learning includes subject matter vocabulary, the content of the lesson and knowing much more. Successful strategies include integrating the new ideas with prior knowledge (d=.93), outlining and transforming (d=.85), summarization and organizing (d=.63). Note, at this phase, memorization has a very low effect (d=.06). It is the skill to learn how to sift out the wheat from the chaff, to develop a coat hanger on which to frame the various bits of information that matter the most at the phase.

Note, what matters is teaching students these skills of outlining and summarizing and not merely giving them a teacher-prepared outline or summary.

Consolidating surface learning

Once a student has begun to develop surface knowledge it is then important to encode it in a manner such that it can retrieved at later appropriate moments. This encoding involves two groups of learning strategies: the first develops storage strength (the degree to which a memory is durably established or 'well learned') and the second develops strategies that develop retrieval strength (the degree to which a memory is accessible at a given point in time; Bjork & Bjork, 1992). Encoding strategies are aimed to develop both, but with a particular emphasis on developing retrieval strength. Both groups of strategies invoke an investment in learning, and this involves 'the tendency to seek out, engage in, enjoy and continuously pursue opportunities for effortful cognitive activity (von Stumm, et al., 2011). Although some may not 'enjoy' this phase, it does involve a willingness to practice, to be curious and to explore again, and a willingness to tolerate ambiguity and uncertainty during this investment phase.

In turn, this requires sufficient metacognition and a calibrated sense of progress towards the desired learning outcomes. Strategies include deliberate practice testing (d=.77), the skill to receive and use feedback (d=.71), spaced versus mass practice (d=.60), and rehearsal and memorization (d=.73). Incidentally, it is worth noting that the effect of memorization in this consolidation phase (0.73) is starkly higher than in the Acquiring Surface phase (d=.06) – demonstrating the differential effectiveness of learning strategies depending on the phase and type of learning as depicted in the model.

Acquiring deep learning

Students who have high levels of awareness, control or strategic choice of multiple strategies are often referred to as 'self-regulated' or having high levels of metacognition. Hattie (2009) described these self-regulated students as 'becoming like teachers', as they had a repertoire of strategies to apply when their current strategy was not working, and they had clear conceptions of what success looks like. Pintrich et al. (2000, p. 547). described self-regulation as 'an active, constructive process whereby learners set goals for their learning and then attempt to monitor, regulate and control their cognition, motivation and behavior, guided and constrained by their goals and the contextual features in the environment'. These students know the what, where, who, when and why to use which learning strategies: they know what to do when they do not know what to do. Successful self-regulation strategies include elaboration and organization (d=.75), strategy monitoring (d=.71), and elaborative interrogation (asking “why” questions, d=.42).

Consolidating deep learning

Once a student has acquired surface and deep learning to the extent that it becomes part of their repertoire of skills and strategies, then there is evidence of ‘automatization’. In many senses this automatism becomes an ‘idea’, and so the cycle continues from surface idea to deeper knowing that then becomes a surface idea, and so on. At this consolidating phase, the power of working with others is most apparent, and high levels of trust are needed so that students can “think aloud”. It is through such listening and speaking about their learning that students and teachers realise what they do deeply know, what they do not know and where they are struggling to find relations and extensions. The successful strategies include seeking help from peers (d=.83), classroom discussion (d=.82), evaluation and reflection (d=.75), talking to others about self-consequences (d=.70), problem-based learning with others (d=.68), self-verbalization and self-questioning (d=.64), being a peer tutor and learning to teach others (d=.54), self-explanation (d=.50, self-monitoring (d-.45) and self-verbalizing the steps in problems (d=.41).

Transfer

There are skills involved in transferring knowledge and understanding from one situation to a new situation. Indeed some have considered that successful transfer could be thought as synonymous with learning (Perkins & Salomon, 2012). There are many distinctions relating to transfer: near and far transfer, low and high transfer, transfer to new situations and problem solving transfer, and positive and negative transfer (Bereiter, & Scardamalia, 2014). Marton (2006) argued that transfer occurs when the learner learns strategies that apply in a certain situation such that they are enabled to do the same thing in another situation when they realize that the second situation resembles (or is perceived to resemble) the first situation. He claimed that not only sameness, similarity, or identity might connect situations to each other, but also small differences might connect them as well. Learning how to detect such differences is critical for the transfer of learning. As Heraclitus claimed, no two experiences are identical; you do not step into the same river twice. Indeed, the effect of detecting similarity and differences between the current and new problem is high (d=1.32), as is seeing patterns between old and new situations (d=1.14).

Rather than solving one problem then rushing to solve the next one, a student is well advised to pause, then compare and contrast each problem: indeed this seems key to the transfer process. The model (see Figure 2) proposes that Transfer is a skill that, like other skills, can be taught. Consequently, it depicts the falsifiable hypothesis that the learning of transfer may have Acquisition and Consolidation phases, and that strategies for learning transfer may be differentially effective depending on which of these phases is applicable. Despite an absence of evidence for or against this notion, it is worth noting that this idea arose directly from the process of explicating the original model (Hattie & Donoghue 2016), demonstrating one important utility of conceptual models: the generation of falsifiable hypotheses worthy of investigation.

Discussion and Conclusions

There is much debate about the optimal strategies of learning, and indeed we identified over 400 terms used to describe these strategies. Our initial aim was to rank the various strategies in terms of their effectiveness but this soon was abandoned.

There was too much variability in the effectiveness of most strategies depending on when they were used during the learning process, and thus we developed a model of learning to explain and generate predictions about optimal learning strategies and their moderators. Later work investigates methods to assess the various strategies, and to identify the optimal teaching methods related to improving students' knowledge and adaptive use of the strategies. Like all models, Figure 2 is a conjecture, it aims to say much, and it is falsifiable. There are ten major implications.

First, the model posits that learning must be embedded in some content (something worth knowing) and thus the current claims about developing 21st century skills sui generis are most misleading. These skills often are promoted as content free that can be developed in separate courses (e.g., critical thinking, study skills, resilience, growth mindsets). Our model, however, suggests that such skills are likely to be best developed relative to some content. There is no need to develop learning strategy courses, or teach the various strategies outside the context of the content.

Instead, the strategies should be an integral part of the teaching and learning process, and can be taught within this process.

Second, the model includes three major inputs and outcomes. These relate to what the students bring to the learning encounter (skill), their dispositions about learning (will) and their motivations towards the task (thrill). Connecting with prior knowledge, enabling confidence and reducing anxiety, and exposing the criteria of success early in the leaning make the most difference. The optimal is when students are aware of a transparent progression from what they currently know, are able to do, and what they care about to the criteria of success. There needs to be thrill in learning, and hence the drill and skill models, the dominant "tell and practice" model of teaching, and the over saturation of "knowing lots" prescribed by so many curricula documents may mitigate against the presence of this thrill of learning, Like playing many video games, it is the thrill of learning and not the completion of tasks that excite most students – it is not gaining the golden ticket, completing and handing in the work, or getting to the final level that matters; it is the thrill of learning how to play the game. Students will engage in very challenging tasks if the learning requirements are seen to be attainable (with practice and feedback) and not boring; hence the Goldilocks principle of "Not too hard but not too boring" (Lomas et al., 2016).

Third, the model proposes that effective learning strategies will be different depending on the phase of the learning—the strategies will be different when a student is first acquiring the matters to be learnt compared with when the student is embedding or consolidating this learning. That is, the strategies are differentially effective depending on whether the learning intention is surface learning (the content), deep learning (the relations between content), or the transfer of the skills to new situations or tasks. In many ways this demarcation is arbitrary (but not capricious) and more experimental research is needed to explore these conjectures. Although the model is presented as linear it is noted that there can be much overlap in the various phases. For example, to learn subject matter (surface) deeply (i.e., to encode in memory) is helped by exploring and understanding its meaning; success criteria can have a mix of surface and deep and even demonstrate the transfer to other (real world) situations; and often deep learning necessitates returning to acquire specific surface level vocabulary and understanding. In some cases, there can be multiple overlapping processes: learning is iterative and non-linear.

Fourth, the essence of successful use of learning strategies relates to the timing and adaptive choice of strategy. While it is possible to nominate the top 10 learning strategies the more critical conclusion is that the optimal strategies depend on where in the learning cycle the student is located. This strategic skill in using the strategies at the right moment is akin to the message in the Kenny Rogers song—you need to ‘know when to hold ‘em, know when to fold ‘em’. For example, when starting a teaching sequence, it is most important to be concerned that students have confidence that they have a reasonable chance to attain the success criteria, see value in the lessons and can relate it to prior learning and future desired skills, and are not overly anxious about the skills to be mastered. Providing them early on with an overview of what successful learning in the lessons will look like (knowing the success criteria) will help them reduce their anxiety, increase their motivation, and build both surface and deeper understanding.

To acquire surface learning, it is worth knowing how to summarize, outline and relate the learning to prior achievement; and then to consolidate this learning by engaging in deliberate practice, rehearsing over time and learning how to seek and receive feedback to modify this effort. To acquire deep understanding requires the strategies of planning and evaluation and learning to monitor the use of one's learning strategies; and then to consolidate deep understanding calls on the strategy of self- talk, self-evaluation and self-questioning and seeking help from peers. Such consolidation requires the learner to think aloud, learn the 'language of thinking', know how to seek help, self-question and work through the consequences of the next steps in learning. The transfer of learning to new situations involves knowing how to detect similarities and differences between the old and the new problem or situations. There is much less support for standalone learning strategy developing generic working memory skills, critical or creative thinking classes. These classes can have an impact, but there is little evidence that they improve a student's transfer to new content domains. The claim, for example, is that working memory is strongly related to a person's ability to reason with novel information – and needs therefore to be developed within the context of that information.

Fifth, strategies are differentially effective depending on the phase of learning

– early exposure (Acquisition) or strengthening and reinforcing (Consolidation). This distinction is far from novel. Shuell (1990) for example, distinguished between initial, intermediate, and final phases of learning. In the initial phase, the students can encounter a 'large array of facts and pieces of information that are more-or-less isolated conceptually... there appears to be little more than a wasteland with few landmarks to guide the traveler on his or her journey towards understanding and mastery'. Students can use existing schema to make sense of this new information, or can be guided to have more appropriate schema (and thus experience early stages of concept learning and relation between ideas – that is, Deep learning) otherwise the information may remain as isolated facts, or be linked erroneously to previous understandings. At the intermediate phase, the learner begins to see similarities and relationships among these seemingly conceptually isolated pieces of information. The fog continues to lift but still has not yet burnt off completely. During the final phase, the knowledge structure becomes well integrated and functions more autonomously, unconsciously and automatically, and the emphasis is more on performance or exhibiting the outcome of learning.

The sixth set of claims relate to the distinction between surface, deep, and transfer of learning. Critically the model does not assume "surface is bad" and "deep is good", nor does it privilege one over the other. Instead is presumes both are critical: surface feeds into deep, and deep can then feed into transfer, or even back to surface – it is a matter of emphasis, when and for what purpose. As Illeris (2007) noted all learning includes three dimensions" the content dimensions of knowledge, understandings, skills, abilities, working methods, values and the like; the incentive dimension of emotion, feelings, motivation and volition; and the social dimension of interaction, communication and cooperation" (p. 1). Certainly the strategies found to be most effective relate to emotional, social and the cultural dimensions as much as to knowing and understanding. Building proficiency of "capacity change" - not merely due to aging or development processes - is a main responsibility of our educational institutions, and the increasing need to improve surface, deep, transfer along with competencies to respect oneself and others, along with working in teams and interpreting to others what one knows is now all the more critical. It is the proportion, at the right time, for the right gains, for the right reasons of surface and deep that matter much more than one or the other. The model proposes a direction as to ‘what is learning?’ – It is the outcome from moving from surface too deep to transfer. Only then will students be able to go beyond the information given to ‘figure things out’, which is one of the few untarnished joys of life (Bruner, 1996). One of the greatest triumphs of learning is what Perkins (2014) calls ‘knowing one’s way around’ a particular topic or ‘playing the whole game’ of history, mathematics, science or whatever. This is a function of knowing much and then using this knowledge in the exploration of relations and to make extensions to other ideas, and being able to know what to do when one does not know what to do (the act of transfer).

Seventh, strategies for transfer are known and can be taught. It is so important to teach students to pause and detect the similarities and differences between previous tasks and the new one, compare and contrast the similarities in the previous and new problem before attempting to answer a new problem. Too many (particularly struggling) students over-rehearse a few learning strategies (e.g., copying and highlighting) and apply them in situations regardless of the demands of new tasks.

Certainly, the fundamental skill for positive transfer is stopping before addressing the problem and asking about the differences and similarities between the old and new task. This ability to notice similarities and differences over content is quite different for novices and experts and we do not simply learn from experience but we also learn to experience (Marton, Wen, & Wong, 2005; Bransford, et al., 1999). Preparation for future learning involves opportunities to try our hunches in different contexts, receive feedback, engage in productive failure and learn to revise our knowing based on feedback. The aim is to solve problems more efficiently, and also to 'let go' of previously acquired knowledge in light of more sophisticated understandings—and this can have emotional consequences: 'Failure to change strategies in new situations has been described as the tyranny of successes.' (Robinson, Stern, & Stern, 1997, p.84) It is not always productive for students to try the same thing that worked last time. Hence there may need to be an emphasis on knowledge-building rather than knowledge-telling, ~~85~~ and systematic inquiry based on theory-building and disconfirmation rather than simply following processes for how to find some result.

Eighth, the model can help explain why some popular teaching methods, such as most programs based on "deep learning" have low rates of success. For example, there have been 11 meta-analyses relating to problem-based learning based on 509 studies, leading to, on average, a small effect (d = 0.15). It hardly seems necessary to run another problem-based program (particularly in first-year medicine, where four of the meta-analyses were completed) to know that the effects of problem- based learning on outcomes are small. The current model helps explain this seemingly anomalous finding. Problem based learning is too often introduced before the students have sufficient surface knowledge to thence problem solve. When problem-based learning is introduced after developing sufficient surface knowing, (e.g., in later medical years), the effects increase (Albanese & Mitchell, 1993; Walker & Leary, 2009).

Ninth, it may be worthwhile to map various teaching strategies to the phases of the model. We reviewed the 300+ teaching strategies outlined in Marzano (2016) and determined those which most related to each phase of the model. For Surface acquisition the most optimal teaching strategies include notebook review, pictorial notes, summarizing; for Surface consolidation use assignment revision, frequent structured practice, think logs, two-column notes, revising knowledge using the five basic processes; for Deep acquisition use elaborative interrogation, examining support for claims, generating qualifiers, identifying errors of attack, identifying errors of faulty logic, presenting the formal structure of claims and support, providing backing, and worked examples; for Deep consolidation use grouping for active processing, inside outside circle, peer feedback, peer response groups, peer tutoring, student tournaments, think-pair-share, and cumulative review; and for Transfer use classification charts, dichotomous keys, sorting, matching, categorizing, and student- generated classification patterns. The only strategy that appears to cross the various phases is the Jigsaw method, which has very high overall effect sizes (Batdi, 2014, d=1.20).

Tenth, and as much a summary, if a success criterion is the retention of accurate detail (surface learning) then lower-level learning strategies will be more effective than higher-level strategies. However, if the intention is to help students understand context (deeper learning) with a view to applying it in a new context (transfer), then higher level strategies are also needed. An explicit assumption is that higher level thinking requires a sufficient corpus of lower level surface knowledge to be effective—one cannot move straight to higher level thinking (e.g., problem solving and creative thought) without sufficient level of content knowledge..There are learning strategies that maximize the various parts of the learning cycle: students need to create their own set of known learning strategies, be able to meta-cognitively choose a strategy for a given learning experience, be able to evaluate the effectiveness of that strategy, and finally to have the cognitive flexibility to change strategies if one proves ineffective. This fundamental skillset that recognizes learning as a complex, non-linear and time-sensitive phenomenon, can and should be taught.

Acknowledgements

The Science of Learning Research Centre is a Special Research Initiative of the Australian Research Council. Project Number SR120300015.

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Appendix 8:.Irrelevance of Neuromyths

Horvath, J.C., Lodge, J.M., Hattie, J.A.C., & Donoghue, G.M. (2019). The potential irrelevance of neuromyths to teacher effectiveness: Comparing neuro-literacy levels amongst award-winning and non-award winning teachers. *Frontiers in Psychology, 9, 1666*..

frontiers in Psychology

ORIGINAL RESEARCH
published: 11 September 2018
doi: 10.3389/fpsyg.2018.01666

On the Irrelevance of Neuromyths to Teacher Effectiveness: Comparing Neuro-Literacy Levels Amongst Award-Winning and Non-award Winning Teachers

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OPEN ACCESS

Edited by:
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Reviewed by:
Alison W. Arrow, University of Canterbury, New Zealand
Geoff Hollis, University of Alberta, Canada
Melissa Christine Davis, Curtin University, Australia

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Specialty section:
This article was submitted to Educational Psychology, a section of the journal Frontiers in Psychology

Received: *14 February 2018*
Accepted: *20 August 2018*
Published: *11 September 2018*

Citation:
Horvath JC, Donoghue GM, Horton AJ, Lodge JM and Hattie JAC (2018) On the Irrelevance of Neuromyths to Teacher Effectiveness: Comparing Neuro-Literacy Levels Amongst Award-Winning and Non-award Winning Teachers. Front. Psychol. 9:1666. doi: 10.3389/fpsyg.2018.01666

A number of studies have recently demonstrated a high level of belief in 'neuromyths' (fallacious arguments about the brain) amongst trainee and non-award winning educators. The authors of these studies infer this to mean that acceptance of these neuromyths has a negative impact on teaching effectiveness. In this study, we explored this assumption by assessing the prevalence of neuromyth acceptance amongst a group of internationally recognized, award-winning teachers and comparing this to previously published data with trainee and non-award winning teacher populations. Results revealed the acceptance of neuromyths to be nearly identical between these two groups, with the only difference occurring on 2 (out of 15) items. These findings suggest that one cannot make simple, unqualified arguments concerning the relationship between belief in neuromyths and teacher effectiveness. In fact, the idea that neuromyths negatively impact upon teaching might, itself, be a neuromyth.

Keywords: neuromyths, neuroliteracy, educational neuroscience, award winning teachers, teacher training

INTRODUCTION

Howard-Jones et al. (2009) presented the first exploration into the level of 'neuroliteracy' (understanding about the brain and how it functions) amongst novice educators in the United Kingdom. After conducting semi-structured interviews with 158 novice teachers in the United Kingdom, they concluded that interviewed educators demonstrated an alarmingly high level of belief in 'neuromyths' – misconceptions generated by the misunderstanding, misreading, or misquoting of facts established by neuroscientists (Organization for Economic Cooperation and Development [OECD], 2002). These findings have been replicated with varied teacher populations in other countries: including the Netherlands (Dekker et al., 2012), Greece (Deligiannidi and Howard-Jones, 2015), and Turkey (Karakus et al., 2015).

Within each paper, the authors make a number of statements alluding to how they interpret the relationship between these two variables. For instance, Howard-Jones et al. (2009) stated that "trainee teachers acquire. . .ideas about brain function, many of which are potentially detrimental to their practice as teachers" (p. 2). Similarly, Karakus et al. (2015) claim that "ideas about the brain are . . . likely to influence [teachers'] practice in the classroom" (p. 1934). Finally, Deligiannidi and Howard-Jones (2015) argue that "there is good reason … to consider these misunderstandings contribute to poor practice in the classroom" (p. 3910).

Taken together, these quotes suggest that the proliferation of neuromyths likely has a *negative* impact on teacher practice. Interestingly, this is a questionable assumption as none of these studies draw any direct link between neuromyth acceptance and teacher practice. Put simply, there is no evidence to suggest neuromyths have any impact whatsoever on teacher efficacy or practice: it is merely an untested assumption put forward by the authors of the previously mentioned papers. Despite this, this assumption has proven wildly popular and, with no supporting evidence, been used to support the idea that neuroscience and basic brain knowledge should be included in (some argue, a mandatory feature of) teacher training and professional learning in order to improve teacher efficacy (Dubinsky, 2010; Summak et al., 2010; Hardiman et al., 2012; Dubinsky et al., 2013; Dekker and Jolles, 2015). For instance, Karakus et al. (2015) state "Given the high levels of neuromyths amongst Turkish teachers…we recommend greater attention is paid to the brain in initial teacher training and continuing professional development of teachers" (p. 1939).

If we allow for the current *assumption* concerning the impact of neuromyth acceptance on teacher practice, there appears to be a relatively simple way to test its veracity: explore the levels of neuromyth acceptance amongst internationally recognized, award-winning teachers. In other words, inherent in the argument that neuromyth acceptance will negatively impact teacher practice is the inference that effective teachers must have more *correct* knowledge about the brain (or, at least, accept fewer neuromyths). Although exploring neuromyth acceptance levels amongst effective teachers will *not speak directly* to the impact of neuromyths on practice, it will speak directly to the *prevailing assumption* and may help elucidate several parameters to help clarify any underlying relationship.

Accordingly, the aim of this study is to ascertain neuromyth acceptance levels amongst internationally recognized, award-winning educators and compare these to the levels previously reported amongst trainee and non-award winning educators.

MATERIALS AND METHODS

Ethics Statement

This study was carried out in accordance with the recommendations of The University of Melbourne Human Ethics Committee with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki. The protocol was approved by The University of Melbourne Human Ethics Committee.

Participants

Award-winning teacher participants were 50 pre-, primary-, secondary-, and tertiary-school educators from the United Kingdom, United States, and Australia who had won a national or international teaching excellence award between 2013 and 2015. There were 20 males and 30 females. 17 had a Bachelors Degree, 13 a Graduate Certificate, 11 and Masters Degree, and 7 a Ph.D. Average teaching duration for these respondents was 18.56 years (SD = 9.46 years). Teachers worked within the preschool (6), primary (17), secondary (17), and tertiary (10) sectors. Teaching awards include the Australian Award for Teaching Excellence (AU); Australian Award for University Teaching (AU); CCSSO National Teacher of the Year (US); CCSSO State Teacher of the Year (US); National Excellence in Teaching Award (AU); Innovation in Secondary Education (AU); Pearson National Teaching Award (UK); and Vice Chancellor's Award for Teaching (AU).

The responses from 865 trainee and non-award winning teachers were derived from published articles using the same instrument used in this study. This included: 158 teacher trainees with an average teaching duration of 0 years from Howard-Jones et al. (2009), 242 primary and secondary teachers from Dekker et al. (2012: no demographic data related to time teaching included), 217 primary and secondary teachers with an average teaching duration of 15.1 (SD = 9.3) years from Deligiannidi and Howard-Jones (2015), and 248 primary and secondary teachers from Karakus et al. (2015: no demographic data related to time teaching included). Unfortunately, as these studies did not include detailed demographic data, we were unable to obtain degree level statistics from these samples.

Instrument/Procedure

Award-winning teacher participants were contacted directly by researchers via e-mail and were asked for consent to complete a survey as developed by Howard-Jones et al. (2009). In additional to demographic information, the survey contained 15 common 'neuromyth' statements. Participants were asked to read each statement and respond whether they felt each statement was 'correct,' 'incorrect,' or 'don't know.' Participants were not reimbursed for their time.

During the initial mailing, 65 award-winning teachers were contacted. Of these, 48 responded. One week after the initial mailing, a second mailing to 8 new award-winning teachers was conducted. Of these, 2 responded. In total, 73 teachers were contacted and 50 responded.

Analysis

A maximum likelihood factor analysis of the 15 neuromyths was conducted using the answers obtained from award-winning teachers. This was conducted in order to help elucidate and thematic difference in responses between the two groups. Importantly (and unexpectedly) the results of this analysis revealed no meaningful structure to the neuromyths questionnaire (see section "Results"). For this reason, each question was further explored individually utilizing a 2 (award/non-award) $\times$ 3 (correct/incorrect/don't know) chi-square test of independence. For novice teachers, response values were calculated by multiplying the weighted proportion by the total N for each question. Bonferroni corrections for

15 chi-square tests adjusts the overall alpha ($p < 0.05$) to a significant alpha value of 0.0033. Effect sizes presented are Cramer's V (small effect ≤ 0.08; moderate effect ≤ 0.22; large effect ≥ 0.35).

RESULTS

Factor Analysis

Across the 15 items, the estimate of reliability (coefficient alpha) was 0.49. This is below acceptable levels (<0.70). Furthermore, the total amount of variance explained by the first factor (using maximum likelihood extraction) was only 13%; again, below acceptable levels. Thus, the scale can only be considered a series of random responses and the items should not be used to form any sort of composite measure.

Individual Questions

Response proportions and statistics for each neuromyth are presented in **Table 1**. Chi-square analyses revealed no significant difference in response patterns between trainee and non-award winning teachers and award-winning teachers on 13 of 15 items. Effect sizes for 12 of the 15 items was small whilst effect sizes for the remaining three were moderate.

Award-winning teachers were more likely than trainee and non-award winning teachers to (correctly) disagree with statements "*There are critical periods in childhood after which certain things can no longer be learned*" (award-winners 66% disagreed, non-award winners 39%) and "*Children must acquire their native language before a second language is learned; if they do not do so, neither language will be fully acquired*" (award-winners 76%, non-award winners 59%). The effect sizes for these two items were moderate (Cramer's V of 0.174 and 0.149, respectively).

DISCUSSION

If neuromyth acceptance were correlated with teacher efficacy (as has been argued by several prominent Educational

TABLE 1 | Proportion of responses between groups (in percentages) and chi-square statistics for each neuromyth.

	Neuromyth	Non-award winners			Award-winners					
		Yes	*No*	*DK*	*Yes*	*No*	*DK*	Cramer X^2	*p*	V
A	Differences in hemispheric dominance (left brain, right brain) can help explain individual differences amongst learners.	**79**	4	18	**74**	10	16	3.21	0.201	0.058
B	Exercises that rehearse co-ordination of motor-perception skills can improve literacy skills.	**61**	9	30	**66**	4	30	1.57	0.456	0.041
C	Extended rehearsal of some mental processes can change the shape and structure of some parts of the brain.^	56	**11**	33	66	**2**	32	4.34	0.114	0.067
D	Short bouts of co-ordination exercises can improve integration of left and right hemispheric brain function.	**72**	3	24	**74**	4	22	0.19	0.909	0.014
E	Environments that are rich in stimulus improve the brains of pre-school children.	**85**	8	7	**88**	4	8	1.1	0.577	0.034
F	Individual learners show preferences for the mode in which they receive information (e.g., visual, auditory, kinesthetic).^	89	**5**	6	94	**6**	0	2.99	0.224	0.056
G	Children are less attentive after consuming sugary drinks and/or snacks.	**53**	21	26	**70**	16	14	5.52	0.063	0.076
H	Individuals learn better when they receive information in their preferred learning style (e.g., auditory, visual, kinesthetic).	**93**	3	4	**84**	12	4	11.35	0.004	0.110
I	If pupils do not drink sufficient amounts of water (6–8 glasses a day) their brains shrink.	**20**	39	41	**22**	42	36	0.48	0.787	0.023
J	Regular drinking of caffeinated drinks reduces alertness.^	40	**31**	29	40	**32**	28	0.05	0.975	0.007
K	We only use 10% of our brain.	**48**	24	28	**48**	32	20	2.26	0.323	0.049
L	Learning problems associated with developmental differences in brain function cannot be remediated by education.	**19**	61	20	**14**	72	14	2.62	0.27	0.053
M	It has been scientifically proven that fatty acid supplements (omega-3 and omega-6) have a positive effect on academic achievement.	**55**	13	32	**50**	6	44	4.28	0.118	0.067
N	There are critical periods in childhood after which certain things can no longer be learned.*	**51**	39	10	**20**	66	14	17.33	**<0.001**	0.174
O	Children must acquire their native language before a second language is learned. If they do not do so neither language will be fully acquired.*	**33**	58	7	**10**	76	14	12.71	**0.002**	0.149

*Bold = incorrect response; ^reverse coded; *question was not included in Howard-Jones et al. (2009) or Deligiannidi and Howard-Jones (2015). Final n = 490.*

Neuroscientists), then one would reasonably expect to see a lower prevalence of neuromyth acceptance amongst internationally recognized, award-winning teachers than amongst trainee and/or non-award winning teachers. The results in this study indicate that the majority of neuromyths (13 of 15) are equally accepted amongst both groups. This suggests that there is not a clear or obvious relationship between neuromyth acceptance rates and teacher effectiveness, and that any arguments along those lines will require *direct* exploration of the impact of brain knowledge on teacher practice beyond that explored by any paper (including this one) to date.

Furthermore, a factor analysis of the neuromyth questionnaire reveals that the items are largely unrelated and do not contain any underlying structure or pattern. Interestingly, this factor analysis was run with the intention of determining if survey items coalesced into any distinct categories or if they simply lumped under a general 'neuromyth' factor (the intention being to help elucidate any differences identified between groups). The fact that the items included on this questionnaire contain no underlying structure was unexpected, and raises important questions as to what (if anything) this type of questionnaire is really exploring. Accordingly, past studies using this questionnaire (including this one) should be interpreted with caution. Furthermore, future studies interested in exploring this topic should consider developing, testing, and validating a questionnaire with underlying construct validity and sufficient estimates of reliability.

Issues of the factor analysis aside, we did find award-winning teachers were significantly less likely to accept 2 of the included 15 neuromyths than trainee and/or non-award winning teachers ("*There are critical periods in childhood after which certain things can no longer be learned*" and "*Children must acquire their native language before a second language is learned; if they do not do so, neither language will be fully acquired*"). Interestingly, both of these neuromyths appear to concern 'critical periods' during the process of skill acquisition, such that award-winning teachers are less likely to believe there are specific learning trajectories or processes students *must* follow. Although we are apprehensive to read too much into these difference at this point, it would be worth considering the development of coherent, valid questionnaire that directly explores this aspect of teaching/learning in order to determine if there is a true difference between teachers along this dimension. If, indeed, award-winning teachers are less likely to accept the concept of critical periods, then this might point to a worthwhile area of future exploration and remediation.

An important limitation of this study concerns the inability to meaningfully match the two compared groups along specific demographic lines (such as degree earned, years spent teaching, etc.). This shortcoming was, unfortunately, a limitation of the method we utilized (pooling and comparing previously published data lacking specific demographic detail with newly obtained data). Although this does not negate our findings, it does raise questions as to if these findings would change were we able to account for specific age of respondents, time since degree completion, year-level taught, amount of popular science reading done by participants, etc. As such, future and more fine-grained research should be undertaken before the results of this study are interpreted and extended beyond its current form.

Another limitation of this study is the inference that the sample of award-winning teachers included were selected for their general teaching effectiveness. In truth, there is no more way of knowing that an 'award' is correlated with improved efficacy than there is of knowing that the moniker 'teacher trainee' (as used in several of the previous study populations) is correlated with diminished efficacy. It would be desirable for future studies to relate the many dimensions of effective teaching to knowledge about neuroscience and the development of the brain. Along these same lines, it is worth considering what criteria 'judges' utilize when determining recipients of teaching awards. It is certainly possible that these 'judges,' themselves, accept neuromyths and select award recipients based upon the utilization of teaching methods that align with these myths (which could be one reason for our findings). Although this is merely speculative and requires evidence to substantiate, it does open some doors to interesting avenues of future research.

The evidence obtained here does raise interesting questions concerning the importance (some say, necessity) of including neuroscience in teacher education. Seeing as teacher training is a difficult and contested endeavor (Harris and Sass, 2011; Koedel et al., 2015), it would be important to demonstrate that any changes or inclusions to current curricula meaningfully translate into improved teacher practice and/or effectiveness. This is not to say that information about the brain should *not* be included in teacher training program (as doing so may lead to the diminishment of neuromyth acceptance), it is simply to say that there is no evidence to date to suggest what impact brain knowledge has on teacher practice. Furthermore, seeing as our evidence suggests the validity of the currently utilized 'neuromyth' questionnaire may be questionable, it is important that policy and practice not be driven by this evidence until more is understood.

As has been frequently noted that there is a real risk of neuroscience being misapplied in educational contexts (Bruer, 1997, 2016; Horvath and Donoghue, 2016; Horvath et al., 2016). However, in combating this occurrence, it is imperative researchers do not simply create a *different* mythology equally devoid of evidence. It is one thing to demonstrate that acceptance of neuromyths is high amongst teachers across all levels, but it is a different notion to suggest that these myths in any way impact (negatively or positively) upon teaching and learning. When this is combined with the evidence that the currently utilized neuromyths questionnaire may not be valid, it is clear that all studies to date (including this paper) exploring neuromyth levels within education must *not be* interpreted as correlating brain knowledge and teacher practice. It may, indeed, someday be demonstrated that a better understanding of how the brain works may help teachers become more effective; but this evidence remains chimerical and we must avoid substituting it with unfounded inference.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

FUNDING

This work was supported by ARC-SRI: Science of Learning Research Centre (Project No. SR120300015).

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.