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Translating neuroscience, psychology and education: An abstracted conceptual framework for the learning sciences

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Abstract: Educators strive to understand and apply knowledge gained through scientific endeavours. Yet, within the various sciences of learning, particularly within educational neuroscience, there have been instances of seemingly contradictory or incompatible research findings and theories. We argue that this situation arises through confusion between levels of analysis applicable to various disciplines. In this article, we propose a conceptual framework for the science of learning which integrates sociological, psychological, biological and neurological perspectives of learning. This framework seeks to recognise the distinction between *learning*—essentially a complex neurological phenomenon—and *education*, an even more complex sociocultural phenomenon. As such, the framework allows a coherent perspective to emerge that can help resolve a number of key issues. Specifically, we argue that its adoption will (a) provide the science of learning with a foundation to assist in the development of a translational paradigm for neuroscience, psychology and education professionals, (b) enable neuromyths to be more easily identified and (c) help prevent unhelpful debates in the future.

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Gregory M. Donoghue and Jared Horvath are researchers at the Science of Learning Research Centre at the University of Melbourne Graduate School of Education. The SLRC is a Special Research Initiative funded by the Australian Research Council, and is briefed to research the application neuroscience to learning and education. Greg and Jared's research focuses on the translation of biological, neuroscientific and psychological sciences into educational practice, as they seek a fuller understanding of human learning, and how these natural sciences contribute to this understanding. As a cognitive neuroscientist, Jared specialises in how brain structure and function relates to teaching and learning, while Greg's expertise is in psychology, and also specialises in the application of evolutionary biological psychology and neuroscience to human learning and well-being.

PUBLIC INTEREST STATEMENT

Some experts claim that brain-training is effective, and argue that it should be used by educators in classroom. In contrast, educational psychologists and learning scientists claim that such training is ineffective, and should not be used in educational practice. Who should educators believe? Given that educators are experts in education, not psychology or neuroscience, how can they make sense of these differing opinions. This article proposes a conceptual framework that resolves this problem by describing a translation schema that allows for meaningful dialogue between scientists and educators. While teachers can be informed by psychology and neuroscience, these disciplines cannot *prescribe* what teachers do in practice: recognising that educators have a unique expertise in pedagogical practice. In the example of brain-training, we demonstrate how both neuroscientists and psychologists can both be correct in their assertions, and how educators can translate—meaningfully benefit from—this type of research.

Subjects: Neuroscience; Philosophy of Education; School Psychology; Sociology of Education

Keywords: education; learning; teaching; psychology; neuroscience; science of learning; educational neuroscience; translation

1. Introduction

To their credit, 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 paper.

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.

2. 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 organs are integrated, an *organism* is the result, and 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 (Biochemistry);
- Cells specialise and colonise to form organs (Cellular Biology);
- Organs conglomerate and organise into organisms (Physiology, Psychology, Biological Psychology);
- Organisms congregate to form populations (Sociology/Ecology).

Or more simply,

energy → ***matter*** → ***cells*** → ***organs*** → ***organisms*** → ***populations***

3. The framework

We propose that each of these layers can be used to populate an abstracted, multi-layered framework, as described in Table 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 paper.

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—fits into this layer, as would the study of *in vitro* neural networks. Systems neuroscientists, neurologists and computational neuroscientists operate 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

Table 1. Proposed layered abstraction framework 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

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 we argue 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 that 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.

4. Features of the framework

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

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 principal 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*.

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). However, Donohoe, Topping, and Hannah (2012) examined the effects of the programme on 33 students aged 13–14 and 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 strongly 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?"

5. Resolving contradictions with the framework

Earlier in this paper, 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.

6. Future application

Whilst beyond the scope of this present paper, 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:

(1) Definitions of learning ("what is learning?");
(2) Mechanisms of learning ("how does learning occur?");
(3) Learning influences ("what factors can moderate learning?");
(4) Learning interventions ("what interventions can directly enhance learning?");
(5) 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. This 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).

7. 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.

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