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What Can Cognitive Neuroscience Do to Enhance Our Understanding of Education and Learning?

Hon Wah Lee[1,2,*] and Chi-Hung Juan[2,*]

[1]*Graduate Institute of Learning and Instruction, National Central University, Jhongli City 320, Taiwan*
[2]*Institute of Cognitive Neuroscience, National Central University, Jhongli City 320, Taiwan*

The development and popularity of brain science have driven many people to look to the brain for answers to improving learning. Cognitive neuroscience as an interdisciplinary area of research with a focus on human cognition has the potential to connect the brain and education. This paper explores what cognitive neuroscience can (and cannot) do to enhance our understanding of education and learning by examining in greater depth why certain previous attempts to bridge this gap are more successful than others. This paper also discusses the implications of this merge for scientists and educators, and future directions for research in neuroscience and neuroengineering.

KEYWORDS: Cognitive Neuroscience, Brain, Education, Learning.

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INTRODUCTION

The focus of neuroscience is the study of the biological brain. Yet how studying the structure and functions of the brain enables us to understand education and learning may not be as straightforward as in other cross-disciplinary collaborations. With the advance of neuroscientific research and techniques, many people begin to look to the brain for answers to understanding learning and even improving education, but the proposal and attempt to bring together neuroscience and education have drawn a lot of discussion from scholars in the fields of education and various scientific disciplines. The possibility of bridging this gap has thus far been filled with both scepticism and cautious optimism.

When neuroscientific techniques were first applied to the study of human cognition, it raised concerns from educators about how much could be gained about learning from studying the brain. For example, Holt [1] argues that the human mind is very complicated but brain research techniques may only provide us with data at a level so crude compared to the brain activity that studying the mind based on such data is analogous to learning about the ocean by sampling a bucket of water obtained from the ocean. Holt [1] and Fischer [2, 3] also question the extent to which studies carried out in laboratory settings (such as wearing an eye camera with one's head fixed on a chin rest in a reading experiment) can reliably help us make judgments about what people do in real-life situations (e.g., reading that takes place in a school classroom or at home). These concerns highlight the crucial role of reliable brain research tools and methods in assessing cognition and learning if we hope to bring the fields of neuroscience and education closer together.

Other scholars are concerned about the fundamental incompatibility of the two fields of study [4–8], as neuroscience and education have their roots in different philosophies (natural science vs social science) and study humans at different levels of analysis (synaptic vs behavioural). Bruer [4] comments that drawing conclusions from what we know about changes in the brain to guide what we do in a classroom is "trying to build a bridge too far" (p. 4), and Howard-Jones [7] asserts that this "simple transmission model . . . should never be expected to work" (p. 111). Nonetheless, this bridge is not impossible to build.

One possible mediator between neuroscience and education, as some have proposed, is cognitive neuroscience.

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[*] Authors to whom correspondence should be addressed.
Emails: honnes.lee@gmail.com, chijuan@cc.ncu.edu.tw

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Encompassing diverse areas of study including cognitive psychology, systems neuroscience and computational neuroscience, cognitive neuroscience seeks to understand the underlying neural mechanisms of cognitive processes and therefore takes advantage of the interface between brain, mind and behaviour. Developing a more integrated understanding of brain, mind and behaviour is useful for advancing our understanding of education and learning because learning is primarily related to how the brain works to support knowledge construction and skill acquisition whereas education is about providing opportunities and environments for learners to best achieve these goals. Bruer [4, 5] believes that this indirect route between neuroscience and education which is mediated by cognitive psychology would be profitable because, firstly, the connections between cognitive psychology and teaching and learning have already been well established, and secondly, the combination of both methods and models of cognitive psychology and brain research techniques enables cognitive neuroscientists to study how mental functions underlying learning are implemented in the structural properties of our cognitive architecture. Geake [9, 10] is also hopeful that this interface between brain, mind and behaviour made possible by cognitive neuroscience can add another level of understanding to our conception of learning within a bio-psycho-social framework.

Against this background of scepticism and cautious optimism, the goal of this paper is to take a closer look at this connection between neuroscience and education by exploring what cognitive neuroscience can (and cannot) do to help us understand education and learning. This will be done by examining in greater depth why certain previous attempts to bridge this gap are more successful than others. This paper ends by discussing what implications this merge has for scientists and educators, and future directions for research in neuroscience and neuroengineering.

CONTRIBUTION OF COGNITIVE NEUROSCIENCE TO OUR UNDERSTANDING OF EDUCATION AND LEARNING

One primary concept in cognitive neuroscience that is most relevant to our understanding of learning is "neuroplasticity," which essentially means that the brain can be changed after birth as a result of experience or environment. The reassuring fact about neuroplasticity is that the brain can be changed, but it should not be overlooked that it also means the brain can be changed for better or for worse.

Maguire and her colleagues [11, 12] investigated how learning changes the brain in a series of cross-sectional and longitudinal studies involving qualified London taxi drivers. To pass stringent examinations for an operating licence, it typically takes taxi drivers in London 3–4 years to navigate and become familiar with the complex layout of the city. In addition to showing superior knowledge about London landmarks and their spatial relationships, these taxi drivers were also found to have greater gray matter volume in their posterior hippocampi, a region that plays a key role in memory and navigation, which varied as a function of years of taxi driving. Such structural changes in the brain, however, were not observed in non-taxi drivers, suggesting that the differences are likely to be explained not simply by expertise in driving but rather by experience of navigating in a complex,

Hon Wah Lee is currently a Ph.D. candidate at National Central University, Taiwan. He is also an experienced English language teacher and has taught extensively at secondary, post-secondary and tertiary levels in Hong Kong, Taiwan, Bolivia and Australia. In his experience working with many low achievers, he became interested in the question of how to help them learn so as to achieve their full potential. He realised that he also had to understand how the brain learns in order to profitably explore this question. Given his background, Hon Wah is particularly interested in using a cross-disciplinary approach to studying the relationship between learning and the developing brain.

Chi-Hung Juan earned a D.Phil. degree from the Department of Experimental Psychology, University of Oxford, UK and did his postdoctoral training in the Department of Psychology, Vanderbilt University, USA. He was a Taiwan-USA Fulbright scholar and visiting professor of the University of California, Irvine and the University of Oxford. He is currently a distinguished Professor in the Institute of Cognitive Neuroscience, National Central University, Taiwan. The institute was founded in 2003, Chi-Hung Juan is one of the founder members of the institute.

large-scale spatial layout. It would be expected that such effects of extensive learning would be long-lasting, but surprisingly, the observed effects on memory and on the brain can be reversed rather easily and quickly. When the elderly taxi drivers retired after driving for over 30 years and their acquired spatial memory and navigation skills were no longer practised, their brains exhibited a reversal. At just over three years after retirement, their performance on tests of London knowledge fell back to a level similar to the retired non-taxi driver control participants. Their gray matter volume had also become significantly smaller as compared to still-working taxi drivers. In short, their exceptional abilities in memory were almost lost.

In the London taxi driver studies, investigating both the cognitive and neural underpinnings of skill acquisition offers evidence in support of the brain's capacity for neuroplasticity even well into adulthood. The use of structural and functional magnetic resonance imaging (MRI) techniques further reveals that, in the process of learning and becoming expert in a specific skill, both the structure and function of the brain alter in response to constant practice, but the advantage brought about to the brain by years of extensive practice can be reversed as soon as practice ceases.

Some experiential and environmental impacts made to the brain, on the other hand, are less reversible. Meaney and his colleagues have studied how experiences can rewrite the epigenetic code in the brain's genes. They found in a series of experiments with newborn rat pups [13–16] that those who were frequently licked or groomed, and were nursed in the arched-back posture during the first week of life by their mothers grew up to be less easily stressed and more curious to explore in a novel environment than pups who were not. More importantly, these differences in behavioural responses to stress and novelty did not emerge from inheritance of their genetic make-ups. As Meaney and his colleagues discovered, mother-pup interaction altered the expression of one of the genes involved in regulating stress responses, the glucocorticoid receptor gene, in the offspring's hippocampus.

Environmental influence on gene expression occurs not only in rats. That early experiences can leave long-lasting epigenetic marks in the brain can also be observed in humans. Meaney's research team [17] examined postmortem hippocampal samples obtained from suicide victims with a history of child abuse and found that they exhibited decreased levels of glucocorticoid receptor in the hippocampus compared to non-abused suicide victims and non-suicidal controls. This finding corroborates the effect of parental care on behaviour and on epigenetic changes in gene expression in the human brain. The combination of neuroscientific and genetic techniques in these studies allows us to observe the long-term effects of behaviour on the architecture of the brain.

From an educational perspective, these rat and human brain studies offer another dimension of looking at the question of nature and nurture. What unfolds from the above findings is that genetic influence is not deterministic. The environmental context also plays a role in determining one's development. In other words, nature interacts with nurture during development. In the case of early neglect or abuse, variations in postnatal parental nurturance alter the expression of genes in the hippocampus that mediate stress regulation, leading to the formation of lasting individual differences in stress reactivity and even diminished memory capacity [18]. This is relevant to our understanding of education and learning because, as we have discussed, education is about providing opportunities and environments that foster optimal learning, and the above findings highlight the importance of raising public awareness regarding how sensitive and responsive parenting in the early years affects children's psychosocial and cognitive development and the need to integrate early child care and parenting support as elements to support children's learning. Although Meaney's team [19] have also shown that such maternal effects on behavioural and endocrine responses to stress in rat pups can be reversed with cross-fostering by caring mothers, it seems highly unfeasible in humans to randomly remove a neglected or abused child from their biological family. This is where teachers become all the more important, as they are in a good position to identify vulnerable children through day-to-day encounters and provide much needed love and care for these children in the school setting.

In another line of investigation, Mischel and his colleagues [20] studied 4-year-old children's self-control using a delay of gratification paradigm. Children were given a marshmallow and were then asked to wait for the experimenter to return, in which case they could get a second marshmallow. If they preferred not to wait, they could ring a bell to signal the experimenter to return immediately but they would not get another marshmallow. In the subsequent follow-up studies which have spanned over 40 years [21–24], Mischel and his colleagues observed that those who could delay gratification successfully as children were generally better able to cope academically, socially and emotionally as adolescents and as adults than those who were not willing to wait. Similar findings were also reported in another longitudinal study by Moffitt and colleagues [25].

To conceptualise the underlying processes of self-control, they proposed a model called the cognitive-affective personality system [26–28], which posits that the ability to self-regulate is a result of the dynamic interplay of two systems: a "cool" cognitive system and a "hot" emotional system. According to this hot/cool framework, individuals with more effective self-regulation are those who can strategically access the cool system and suppress the hot system as the circumstance demands. For example, children who try to concentrate on the shape of the marshmallow or pretend that it is just a picture (i.e., the "cool" features) are more likely to resist the temptation of eating the marshmallow right away than those who focus on its smell or taste (i.e., the "hot" features).

To investigate the behavioural and neural correlates of self-control, they employed fMRI in a longitudinal follow-up study [24] and used a go/no-go task to measure participants' impulse control, in which there were a cool and a hot condition. Instead of marshmallows, they used emotional human faces as the hot condition and neutral faces as the cool condition. The imaging results revealed that participants who found it difficult to withhold their responses to happy faces showed less recruitment of the right inferior frontal gyrus but more recruitment of the ventral striatum than those who were more successful at controlling their impulses. The right inferior frontal gyrus has been shown to be involved in inhibition and attentional control (the "cool" system), whereas the ventral striatum is associated with emotional or motivational processing (the "hot" system). Together, the findings indicate that self-control is supported by the ventral frontostriatal circuitry, which involves an interaction of both the cool and hot systems as proposed by the cognitive-affective personality system.

In this example, the cognitive model proposed by Mischel and his colleagues provides a framework that constrains explanation for the behavioural findings obtained from the delay-of-gratification paradigm, whereas the use of fMRI helps to delineate the neural mechanisms involved in self-control by building on the mapping of brain functions made possible by previous neuroscientific studies.

What educators can learn from this line of investigation is that self-control is important because not only does it appear to be a rather stable personal characteristic but it also has predictive validity for one's academic success and life outcomes. Given its importance, parents and teachers should be concerned with how they can foster in children the ability to regulate themselves. Despite the stability of self-control, research has shown that it is amenable to intervention even very early in life. Mischel and colleagues [28] found that manipulating how children mentally represent a marshmallow, such as cueing them to think about the marshmallow as a framed picture or its cool, informational features, can significantly increase their waiting time. Training children to employ cognitive and attentional deployment strategies such as mental representations is a way to improve their self-control. In addition, some preschool programmes that emphasise the training of self-control skills within the regular curriculum have also proven effective in helping at-risk children succeed academically [29]. Educators should rethink how the school curriculum can be adapted or redesigned to encompass not only academic subjects but also self-control strategies to bring about more successful learning experience.

The three lines of investigation presented above represent some successful attempts in forging a meaningful collaboration between neuroscience and learning. Their successes lie in a number of factors. Firstly, many of these efforts originated from an in-depth observation of a real-life behaviour, which gradually evolved into a research endeavour that took many years to develop. Secondly, these research endeavours integrated a multitude of methods in studying brain, mind and behaviour, and provided interpretation of results with evidence across different levels of analysis. Thirdly, the use of brain research tools for investigation was often preceded by an animal model or the formation of a cognitive model that describes the behaviour in sufficient detail and precision.

MISUSE OF NEUROSCIENCE IN EDUCATION AND LEARNING

The efforts described above are certainly highly valued and have enhanced our understanding of learning in a broader sense. However, other attempts at linking neuroscience and education are discouraging and can even be considered misuse of brain science in learning. For example, because of the overhyped "right-left brain theory" in the media, many people including parents and teachers have come to believe that the two sides of the brain are responsible for very different functions and should be trained separately: language and numbers for the logical left brain, and music and images for the emotional, artistic right brain. This way of viewing the brain or categorising learners has been taken fully on board by many parents and teachers without realising that the concept of brain lateralisation originally came from observations in split-brain patients who suffered from epilepsy [30–31].

These patients had their corpus callosum surgically separated to control for interhemispheric spread of epilepsy. It was found that when the left and the right hemispheres were unable to communicate with each other, patients were only able to see and describe an object presented to the right visual field (which is processed by the left hemisphere) but were unable to name it verbally if it was presented to the left visual field (which is processed by the right hemisphere) even though they could give a non-verbal response by pointing to a similar object. Further studies involving split-brain patients gave rise to the idea that the left hemisphere specialises in language functions while the right hemisphere visual-spatial functions. Extrapolating such findings to healthy humans to suggest that there is left/right brain dominance misses an important point that the two hemispheres of the brain in healthy humans, unlike in split-brain patients, are connected anatomically and functionally by the corpus callosum. While there are data suggesting that the two sides of the brain process information differently and that certain functions are lateralised, the corpus callosum enables exchange of information between the two hemispheres such that the brain works as an integrated whole [32]. In addition, the classification of and training for right-brain or left-brain learners are problematic because there is no easy mapping between a task and hemispheric functions. A task that is thought to engage one hemisphere also likely involves the other. For example, the processing of language involves the left hemisphere in processing grammar and the right hemisphere in processing orthography and phonology. It is also evident from numerous neuroscientific studies that many different areas in both hemispheres of the brain are activated even when we perform a simple task such as pointing our finger.

As can be seen in this and many other examples [for a detailed discussion of brain myths, see Refs. [4, 33–35]], a lot of popular brain myths are the unfortunate result of "over-simplifications of some neuroscientific findings [9]." Other brain myths have come from media coverage of neuroscientific findings that were selectively biased [36]. These myths and many so-called "brain-based" parenting tips and teaching ideas derived from such oversimplified or biased reports have become popular and widely accepted for one major reason: they appear to be able to provide seemingly easy, workable solutions to educational problems faced by parents and teachers that they cannot readily solve (such as raising a child's score or improving a child's attention). The anticipation for quick-fix solutions is exactly where the problem lies.

What cognitive neuroscience, or neuroscience, can tell us (at least at the present stage) is largely descriptive rather than prescriptive, as demonstrated in the research studies above. However, it cannot possibly and should not be expected to answer such educational questions as how to choose a preschool based on findings from brain development as many would have hoped [4]. Neither can it offer quick-fix solutions nor ready-made recipes for teaching that can be adopted universally [33, 37].

SUCCESSFULLY BRIDGING THE GAP BETWEEN COGNITIVE NEUROSCIENCE AND EDUCATION: HOW?

A Right Frame of Mind Is Needed in Viewing the Integration of Neuroscience and Education

The juxtaposition of the research endeavours presented earlier and the issue of brain myths described just now contrasts what progress researchers are making and what the public expect with regard to applying neuroscience to informing education. In the research domain, combining neuroscience and education inevitably takes a slow, gradual process as such attempts need to be built on observations, theories and models, and involve the integration of multiple disciplines. In contrast, the public's view that they can draw conclusions from brain research that are immediately relevant to their educational needs, unfortunately, appears overly simplistic, and has often led to high but unrealistic expectations of what this joint venture can bring [3, 38]. Therefore, the first step to successfully integrating brain research and education depends crucially on all stakeholders having a right frame of mind towards the potential of this collaboration. This could be fostered, in part, by an increased awareness and understanding of the current progress in brain research and its application to educational issues.

Raising Awareness and Improving Communication

Clearly, the crux of the problem of brain myths is that the public, especially parents and teachers, are misinformed or ill-informed. Much about the current findings of the relationship between the brain and learning is far from fully understood, because not only is there a gap between the nature of neuroscience and education that needs to be bridged, but there also exists a gap between what neuroscientists know about education and what educators know about neuroscience [34]. To bridge this gap between neuroscientists and educators, many scholars have emphasised the need for reciprocal interaction between researchers of the two fields, which should take place at two levels: to mutually inform [4, 10, 39], and to mutually scrutinise during the transfer of concepts [3, 8].

However, this interaction would be established on the foundation that they can understand each other in the first place. Because neuroscience is a highly specialised domain, to ensure that educators and other non-specialists are ready to participate in discussion with neuroscientists, it is of great importance for neuroscientists to communicate their research in ways that are digestible to the untrained audience [40] yet at the same time not oversimplified as to become misleading [34]. Communication of findings should not be restricted to academic journals but should also be via other channels that are more accessible by the wider community.

Directions for Future Research in Cognitive Neuroscience

From the discussion earlier, concerns from scholars about the difficulty in bridging the gap between neuroscience and education are related to the intrinsic differences between the two fields of study, the research settings, and the level of details in the data we can obtain from brain research. Apparently, future research in cognitive neuroscience should emphasise these three aspects in order to address the scholars' concerns.

Brain Research Based on Cognitive Theories and Models

One present contribution of cognitive neuroscience to our understanding of learning is its description of neural mechanisms underlying different cognitive functions. Bruer [5] believes that neuroscience might also help advance our understanding of learning by providing more details at the neural level to help improve and refine cognitive theories and models, such as in the case of the hot/cool model in delay-of-gratification research. There are two relevant points future cognitive neuroscientific research could emphasise: firstly, it could aim to provide a finer level of details about cognitive functions by studying their underlying neural circuitry at the level of subcomponent skills based on existing cognitive models developed in cognitive psychology. Secondly, it could also move beyond establishing mappings between brain areas and cognitive functions to investigate how activation patterns are related to learning.

Research in Classroom Settings

With regard to the concerns about the reliability and generalisability of data conducted in laboratory environments, future brain research could consider to be conducted in classroom settings [2, 3]. One of the goals of this research could be to re-test in a classroom setting what has previously been found to work in a laboratory [37]. However, several issues have to be tackled when planning and conducting such experiments in the classroom. A lot of the equipment for brain recording or imaging is not easily portable and requires that the participant be wired to a machine. How could this equipment be transported to a school and set up in a classroom that is less susceptible to interference from the surrounding environment or the participant's bodily movement while at the same time without making the participant feel unnatural or uneasy, and without causing inconvenience to the teacher? In addition, execution of such experiments in a large class or in a group setting may be problematic and time-consuming, especially when young children are involved. How can it be ensured that all the participants are following the instructions given by the experimenter and that the data obtained are reliable? These questions become critical when the setting of experiment is changed from the laboratory to the classroom.

Development of Neuroengineering Tools

From the perspective of neuroengineering, new breakthroughs in brain recording and imaging tools would be vitally important. As can already be seen, conducting brain research in the field of practice would certainly require new recording and imaging technologies and equipment be designed with greater portability, functionality and user-friendliness in mind. While it is understandable that new tools take time to develop, future research in the short term should aim to improve technologies that can overcome the limitations of existing research tools. This includes capturing brain activity in greater levels of precision in terms of both temporal and spatial resolutions, reducing the risk associated with some of these tools (such as positron emission tomography), and simplifying the process and shortening the time required for data output and analysis. Advances in neuroengineering techniques, predictably, also depend on advances in our understanding of the brain. The more we understand neural structures, functioning and computations, and how development, diseases and damages to the brain affect cognition and learning, the more successful we are in developing potentially useful techniques and applications for neuroeducational research. Therefore, a concerted effort that involves neuroscientists and other professions including clinicians, physicists, and mathematicians is not only useful but also necessary to drive neuroengineering breakthroughs.

In addition to addressing the three concerns above, future research in cognitive neuroscience could also pay closer attention to questions that are more directly relevant to educators, such as improving student learning. For example, the taxi driver studies indicate a close connection between memory and learning and highlight the need for constant practice in maintaining or even improving one's memory capacity. The notion of memory training would be an area of interest for future research. There is some recent evidence [e.g., Ref. [41]] suggesting that working memory could be improved by adaptive and extended computerised training, with benefits observed in changes in brain activity in associated brain regions and improvements in other non-trained cognitive tasks. To ensure that such training can be successfully applied to education, questions such as the mechanism through which training leads to improvements in memory, the optimal duration of training, the effects on people of different ages and sexes, the extent of improvement that can be achieved, and how long the improvement will last would all need to be answered by future research.

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