Chapter 1

Introduction

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The Nature of the Discipline

> Education is about enhancing learning, and neuroscience is about understanding the mental processes involved in learning. This common ground suggests a future in which educational practice can be transformed by science, just as medical practice was transformed by science about a century ago.
>
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The mission statement of the Centre for Educational Neuroscience in London, the affiliation of all but two of the lead authors in this book, states how this transformation can be brought about:

What: Our vision is to bring together three previously distinct disciplines [education, psychology and neuroscience] – to focus on a specific common problem: how to promote better learning. This will mean building a new scientific community and a new discipline, educational neuroscience.

Why: We now understand better how learning organizes and reorganizes the brain, but there is very little research so far that has had an impact on educational delivery. What is lacking is a body of researchers who are expert in education, psychology, and neuroscience, and to create these researchers is a primary aim of the project.

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How: We believe we can do this by building on existing research collaborations and creating new initial training, post-graduate research, and continuing professional development opportunities for becoming expert in educational neuroscience.

Impact: Bringing education, psychology, and neuroscience together can help in designing better learning environments through the lifespan, and this will lead to more fulfilled and more effective learners.

Three Disciplines: Education, Psychology, Neuroscience

The goal of educational neuroscience is to work out how all learners can be helped to achieve their learning potentials and to make learning more effective for all learners. This has meant in practice that education seeks answers to two main questions.

What are the sources of individual differences in learning?
What are the optimal contexts for the learner?

In an attempt to answer these questions, educational neuroscience has evolved through three key phases of enquiry, which we discus in turn below. See Figure 1.1.

Phase 1. Education and psychology

Prior to the emergence of educational neuroscience as a separate discipline, in what we call Phase 1, educational research had a long history of collaboration with

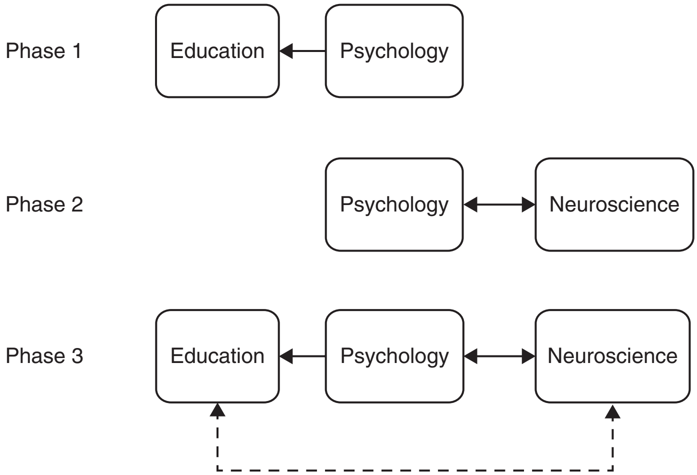

Figure 1.1 Three phases in the emergence of educational neuroscience.

psychology in trying to achieve these goals. This is especially true in curriculum relevant areas such as learning to read and learning mathematics. Psychology first pointed to two main sources of individual differences in learning. First, there were differences in intrinsic cognitive capacity, for example as measured by IQ tests or tests of working memory, and more recently differences in cognitive styles. Another approach has revealed evidence for domain-specific cognitive differences in language acquisition (see Chapter 6), learning to read (see Chapter 7) and learning arithmetic (see Chapter 8). Second, psychological as well as sociological studies revealed experiential sources of individual variation, for example differences in home environment using socioeconomic status or parental education as proxy measures (e.g., Melhuish et al., 2008). Finally, with regard to optimal learning contexts, psychology has provided methodologies for investigating and comparing teaching methods, but it has also made proposals, mostly for mathematics and reading, and to some extent for science.

In mathematics, there was the classic debate between Thorndike and Brownell. In *The Psychology of Arithmetic*, Thorndike (1922) took ideas from associationist theories of psychology, and emphasized drilling simple number bonds. In the 1930s, Brownell, in several important papers, applied psychological ideas about meaningful practice to how math should be taught. In the 1950s and 1960s, Piaget's "constructivist" theories about the nature of cognitive development were very influential. Constructivism emphasizes the child's construction of new schemas (accommodation) when new stimuli cannot be understood using existing schemas (see Chapter 8).

In the case of learning to read, perhaps the most striking impact of psychology is in differentiating dyslexic learners from other learners. Here careful psychological assessment revealed that some children found it hard to learn to read despite good vision, high general intelligence, appropriate teaching, and supportive home environment. Critically, it was found that dyslexic learners suffered from a deficit in analyzing the phonological structure of their language and indeed that phonological training could help (Bradley & Bryant, 1978).

Nevertheless, the debate continues as to whether there is a single underlying phenotype (Elliott, 2005) or whether there are a variety of separable causes of delays and differences in learning to read. Much ink has been spilled in the so-called "reading wars" about which method of teaching reading is most effective. Evidence, until recently, has been entirely based on psychological studies of reading performance. On one side, there are those who have proposed the *whole-word* or whole-language method, in which letter–sound associations are not drilled, but rather children are encouraged to recognize whole words, sound them out, and interpret them. On the other side, there is *phonics*, based precisely on drilling letter–sound correspondences (Ehri, Nunes, Stahl, & Willows, 2001) Unfortunately, many proponents of the two approaches appear to have a political agenda in which left-leaning child-centered proponents prefer the former, and conservative exam-focused proponents prefer the latter. Of course, in an orthography such as English, with many irregular and exceptional pronunciations, the learner needs to have a grasp of both letter–sound correspondences and whole-word pronunciations and meanings. Learners certainly need to know that *pint* is not pronounced to rhyme with *print*. It may be that it will be helpful for the teacher to encourage the learner to recognize whole letter strings, rather than simply insist on sounding out the letters. Nevertheless, children can and do learn to read irregular and exception words by "self-teaching": that is, by using context to figure out what must be meant and thereby get a plausible pronunciation of *pint*, which will then be stored in the mental lexicon of meaningful letter strings (Share, 1995).

Phase 2. Psychology and neuroscience

This phase is characterized by the collaboration between neuroscience and the cognitive, affective, and developmental branches of psychology, to create cognitive neuroscience. In the course of this collaboration, questions arising from education were raised, notably in the neural basis of reading and its disorders, and in mathematics and its disorders, but also in more general issues of attention, executive function, and memory.

The neural underpinnings of cognition and learning in particular have also been the subject of studies of neurological patients. This is perhaps most striking in the case of learning and memory, where selective deficits in patients revealed much about the structure of memory, distinguishing short from long-term memory, declarative from procedural memory, encoding from retrieval, and so on. Even the first steps in revealing the neural bases of curriculum-relevant cognitive processes owe much to the study of patients. The identification of selective reading and spelling problems and evidence for their neural basis dates back to Dejerine in 1892, and modern multiroute models of normal reading were due initially to studies of patients (see Shallice, 1988, for the classic account). Similarly, the basic anatomy and functional organization of mathematical cognition was identified from studies of selective deficits in patients (Caramazza & McCloskey, 1987; Dehaene & Cohen, 1995; Warrington, 1982).

However, the critical impetus for the most relevant aspect of neuroscience for education, *cognitive neuroscience*, came with availability of *in vivo* imaging of neural processes as they happened (see Chapter 2 for a discussion of these methodologies). Neuroimaging has revealed important aspects of domain-general cognitive processes, such as performance on IQ tests, even the developmental trajectory of verbal and non-verbal IQ (Ramsden et al., 2011) and the neural basis of verbal working memory (Paulesu, Frith, & Frackowiak, 1993) and spatial working memory (Petrides, 2000; van Asselen et al., 2006). Other domain-general capacities that contribute to individual differences, such as attention and goal-directed behavior, social and emotional development are now better understood from neuroimaging studies (see Chapter 2). The capacity to understand other minds has also become clearer (see Frith, 2007, and Chapter 10).

Advances have also been made in curriculum-relevant cognitive capacities. For example, the reading network in the brain as revealed by neuroimaging clearly links visual recognition in the inferior temporal region with speech in the inferior frontal gyrus and with word meanings in the middle temporal lobe. This has enabled a better understanding of individual differences in the ability to learn to read in dyslexia. This has been shown to be related to abnormalities in this network: decreased activation in the left inferior temporal region (Paulesu et al., 2001) and abnormal structure in the left middle temporal lobe (Silani et al., 2005). These findings may help to resolve the skepticism that still surrounds the classification of learners as dyslexics.

Note that, without neuroimaging, it might be thought that learning different orthographies, such as alphabetic English or Italian as compared with character-based Chinese or Japanese, might depend on very different neural circuits. However, we now know from neuroimaging that all orthographies depend on similar neural networks (Dehaene, 2009) and indeed that dyslexia is due to similar neural abnormalities (Paulesu et al., 2001).

It has now become feasible to carry out large-scale studies of the development of the brain, and to understand better the genetic and environmental factors that affect it.

Phase 3. Emergence of educational neuroscience

Phase 3 is where we are now: we are seeking to use neuroscience to inform educational practice as a way to improve learning. In 1997, John Bruer famously argued that this was “a bridge too far.”

> Currently, we do not know enough about brain development and neural function to link that understanding directly, in any meaningful, defensible way to instruction and educational practice. … There is a well-established bridge, now nearly 50 years old, between education and cognitive psychology. There is a second bridge, only around 10 years old, between cognitive psychology and neuroscience. This newer bridge is allowing us to see how mental functions map onto brain structures. When neuroscience does begin to provide useful insights for educators about instruction and educational practice, those insights will be the

> result of extensive traffic over this second bridge. Cognitive psychology provides the only firm ground we have to anchor these bridges. It is the only way to go if we eventually want to move between education and the brain.

Bruer based this position on critiques of three aspects of very basic neuroscience usually derived from studies of non-human species: the time course of *synaptogenesis* and *synaptic pruning*, *critical periods* for learning, and the role of *enriched early environments*. He quite sensibly notes that the evidence from these aspects is not sufficient to inform formal education. However, Since Bruer's (1997) paper, there has been rapid expansion of the "pontoon" between the two bridges – cognitive neuroscience. This discipline deploys the resources of brain imaging to develop and refine our understanding of cognitive processes, including those that underpin educational attainment, such as working memory and learning processes, and also curriculum-relevant cognitions involved in language, reading, motivation, and mathematics. This in itself would still be the two-bridge solution that Bruer alluded to.

In 2005, *Nature* published a skeptical editorial questioning the contribution that even cognitive neuroscience could make to education. It warned

> Researchers are planning to use magnetic resonance imaging to "look under the hood" at the development of skills such as numeracy and reading. It's fascinating stuff, but how the results will inform educational practice remains, for now, largely a matter of speculation. Making meaningful connections between brain activity and behaviour is difficult, even under controlled lab settings. Brain imaging is seductive, and has an unfortunate tendency to spawn breathless, overreaching media coverage. Care will be needed to ensure that these projects don't encourage ill-informed "experts" to design yet more pseudoscientific educational tools…. There's also a strong case for putting the educational tools derived from research in neuroscience to more rigorous empirical tests. For instance, researchers who have evidence that dyslexics have problems with auditory processing have developed a program called Fast ForWord to help them learn to read. But the scientists' company is now marketing the software as a learning aid for children with no specific reading deficits, before they have gathered evidence that it helps anyone other than dyslexics. For now, providing this sort of evidence is where the emphasis should remain (Editorial, 2005, p. 1138).

Nevertheless, these new methodologies have enabled us to explore both individual differences in children and education in new ways, suggesting a direct bridge from neuroscience to education. For example, dyslexic readers can be identified through abnormal neural structures and patterns of activation in the reading network (see Chapter 7), even in very young children before they have begun learning to read using neural responses to speech sounds (Lyytinen et al., 2001). Dyscalculic learners can be identified by abnormal neural structures and patterns of activation (see Chapter 8), and these can turn out to be more discriminating than purely behavioral measures (Dumontheil & Klingberg, 2011). Even individual differences in language development (see Chapter 6), reasoning, and social and emotional development (see Chapters 10 and 11 respectively) can also be revealed by neuroimaging. Moreover, links between genetics and neuroimaging, as well as between genetics and cognitive capacity, are strengthening very rapidly (see Chapter 4).

In fact, new methodologies have enabled scientists to plot the developmental trajectories with much more precision than previously. It will become possible in the near future to identify not just neural differences at a particular ontogenetic time point, which may resolve and be simply a delay in development, but also track differences in the developmental trajectories of educationally relevant cognitive functions. It is possible to use mathematical models of trajectory differences to classify learners, and these "learner models" can inform the design of individualized learning contexts in teaching and in learning technologies (see Chapter 3).

Of course, three disciplines are involved, each with their own methodologies, that cannot easily be unified. Therefore, the critical move is what Laurillard has termed "methodological interoperability" (Laurillard, 2007). That is, although the methods of the three disciplines are different, it is possible, and indeed necessary, for each discipline to test the findings of the others. For example, when the cognitive neuroscience theory leads to new pedagogic design, the theory will be tested by more effective learning. More generally, methodological interoperability can be mediated through explicit computational models of a learning process (see, for example, Chapter 3).

Issues and Problems in Developing Educational Neuroscience

The earlier sections of this chapter have spelled out something of the objectives of educational neuroscience. From a *scientific* perspective, the rationale is clear cut, even if the collaboration between – and ultimately integration of – disciplines that it requires presents a range of theoretical and methodological challenges. The diversity of empirically driven theorizing that there has been about learning over the past 150 years can be seen as an indication of the highly complex nature of learning-related phenomena, which for a long while seemed as if they could only be captured in fragmentary fashion. More recently, however, educational psychologists and cognitive neuroscientists have recognized that it is possible to build more integrated models of learning, which do better justice to this complexity by bringing together social and cognitive or cognitive and neural processes within single accounts (for examples of the former, see Philips & Tolmie, 2007, or for the latter, Klingberg, 2010; McNab et al., 2009). If we want to achieve any full account of learning, the logical conclusion is that this will depend on bringing *all* of these strands together in a nonreductionist framework that retains description at the environmental, cognitive, and neural levels, and seeks to understand how these interact with and impact on each other to produce observed outcomes in both formal and informal educational settings. It is this framework that educational neuroscience aims to deliver.

The picture becomes more complex, however, when we turn to *educational* perspectives on the purpose of this enterprise. Education is itself a hugely complex activity with social, economic, political, and individual goals – and a corresponding variety of views on how successful outcomes should be defined. There are in fact some interesting (and, as we shall see, potentially useful) parallels between education and public health (cf. the opening quote in this chapter): defining precisely *why* we promote either is difficult, beyond perhaps a central concern with enabling populations to realize their potential either intellectually or physically, and removing avoidable impediments to this outcome. Nevertheless, despite this fuzziness as to end purpose, it seems reasonable to argue that a full scientific understanding of learning processes and the constraints upon them, and the optimal coordination of this understanding with teaching practices, are shared concerns for educators *and* researchers. The implication is that *translational* research in this sense and the implementation of its lessons are ultimately the fundamental objectives of educational neuroscience. The further implication is that at present the key building blocks necessary to achieve this are held by diverse communities, and not just scientific ones, but also those involving educators, administrators, and policy makers, since they too will have crucial parts to play if genuine translation is to happen.

A serious analysis of what putting these building blocks together is likely to require is critical if we are to understand how to progress, but such an analysis suggests that the scientific challenges may actually be less than the organizational ones. The development of public health as a discipline and a practice provides some indication of what may be involved, as well as some clues as to the structures that we may need to evolve in order to achieve our translational objectives. The origins of modern public health are frequently traced to the work of John Snow during the 1854 cholera outbreak in London. Polluted water and poor waste disposal had long been recognized as being involved in the occurrence of certain forms of disease, but up to this point thinking on the mechanism involved was dominated by miasma theory – essentially the notion that the origin of these diseases lay in airborne emanations from rotting organic matter. The response to outbreaks of disease was therefore driven by concerns with the circulation of air, the location of cemeteries, and so on. Snow's application of germ theory (which had by then gradually garnered a range of supportive evidence) suggested instead that specific microorganisms were responsible for the spread of cholera. This led in turn to his identification of a polluted public water well as the source of the outbreak. This notable success resulted in a rapid extension of germ theory to a range of infectious diseases, a marked growth in public sanitation works, and over the ensuing decades a broadening of activity to include the development of programs relating to public education (e.g., on infant health), vaccination, road safety, occupational safety, and drug control, to cite but a few instances. Public health is now an established part of daily life in developed countries, and an explicit objective of developing ones due to the growth of governmental and international agencies promoting good practice (e.g., the Surgeon-General's office, and the World Health Organisation).

If the translational goals of educational neuroscience parallel those of public health science, then the implication would seem to be that we should (a) begin by targeting a key area of educational need where good theory is able to make an obvious difference, (b) build outward from this initial example via core teams of individuals representing the different contributing strands of activity (i.e., the equivalent to epidemiologists, biostatisticians, local and national government officials, and health service professionals), whose activity is focused on mutually identified areas of need or risk and methods of counteracting these, (c) promote public knowledge of effective practices (without necessarily worrying *too* much about grasp of why these are effective), and (d) let governments take control ultimately, whilst continuing to feed them good, relevant evidence. The key step in this sequence is almost certainly the second one, which depends on building a consensus across key players in multidisciplinary teams within different professional backgrounds, based on (within bounds) shared knowledge of the relevant science – whilst as far as possible avoiding bias towards any one approach which may undermine that consensus.

This is a complex and difficult balancing act. To start with the science itself, the public health model suggests that researchers have a critical role to play in providing reliable and systematic evidence that can steer effective action. However, educational neuroscience research to date is piecemeal and unevenly developed, with much work on dyslexia that is beginning to inform both remedial and mainstream teaching of literacy (see, e.g., Hulme & Snowling, 2009), but few other areas approaching this level of activity, and some (e.g., conceptual growth in science, gifted and talented children) having been addressed by only a handful of researchers. Arguably, of course, public health science was in a similar position in the 1850s, but it did at least have a unifying framework in germ theory that had amassed supporting evidence in a range of areas of work, and which was capable of driving further work. It is hard to point to any framework within educational neuroscience that has similar coherence; to the extent that there is a consensus across researchers, this is based primarily on a shared belief that a full understanding of learning processes demands consideration of the neural level, but not what form the resulting models or framework should take. A consensus of this kind will be hard to achieve without a more coordinated program of research, covering typical *and* atypical learning in a range of key curriculum areas including language and literacy, number and mathematics, conceptual development and causal understanding in science, and socioemotional development. Only by garnering evidence that encompasses a breadth of phenomena using the different disciplinary approaches at our disposal – including intervention work that shows it is possible to bring about specific outcomes – is a bigger picture likely to emerge. One purpose of this book is to encourage the development of a research program of this kind, by illustrating something of what its different elements will look like.

Equally important is the need to progress as a community in a number of different senses. One aspect of this will be researchers from different disciplinary backgrounds working as equal partners, as discussed earlier. The research community needs to become coherent and self-sustaining, however, and this entails not just dialogue and collaboration between existing researchers but the creation of a transdisciplinary environment for the training of students and researchers, who will become the first fully fledged educational neuroscientists by dint of having been schooled to think about the field holistically from the outset.

As noted already, though, to be effective we need to recognize that researchers can only be one part of a wider community of engagement and exchange that helps set the research agenda, and maintains a focus on the implications for practice, including delivery. This wider community will need to encompass teachers, trainee teachers, teacher training agencies, professional educational and school psychologists, speech and language therapists, pediatric neurologists, and members of other professions involved in implementing evidence-based support for learning and remediation of learning difficulties. Moreover, if we take the public health model seriously, then the function of this wider community extends far beyond an advisory or consultative role: it needs to be an active partnership of researchers and professionals working *together* to identify issues, improve understanding through rigorous research, and develop solutions. In other words, practitioners will need to be involved at the heart of the research – and researchers will need to engage with issues of delivery. The implied roles are largely unfamiliar to all concerned, so even setting up a small number of functioning teams will require members to make an unusual commitment, which may need to be based in the first instance on belief in the potential of the work rather than substantial concrete evidence of benefit.

Finally, there will also need to be engagement with policy makers and policy shapers, in order to help ensure that educational neuroscience has socially perceived value, and that team members are therefore in some sense sanctioned to contribute to the development and deployment of novel forms of provision. Given an environment within which politicians and policy specialists are subjected to constant streams of lobbying by organizations with competing vested interests, success on this front will depend on standing out in some way – hence the importance of good science and a convincing application based upon it. If this was true for public health science, it is even more so now.

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