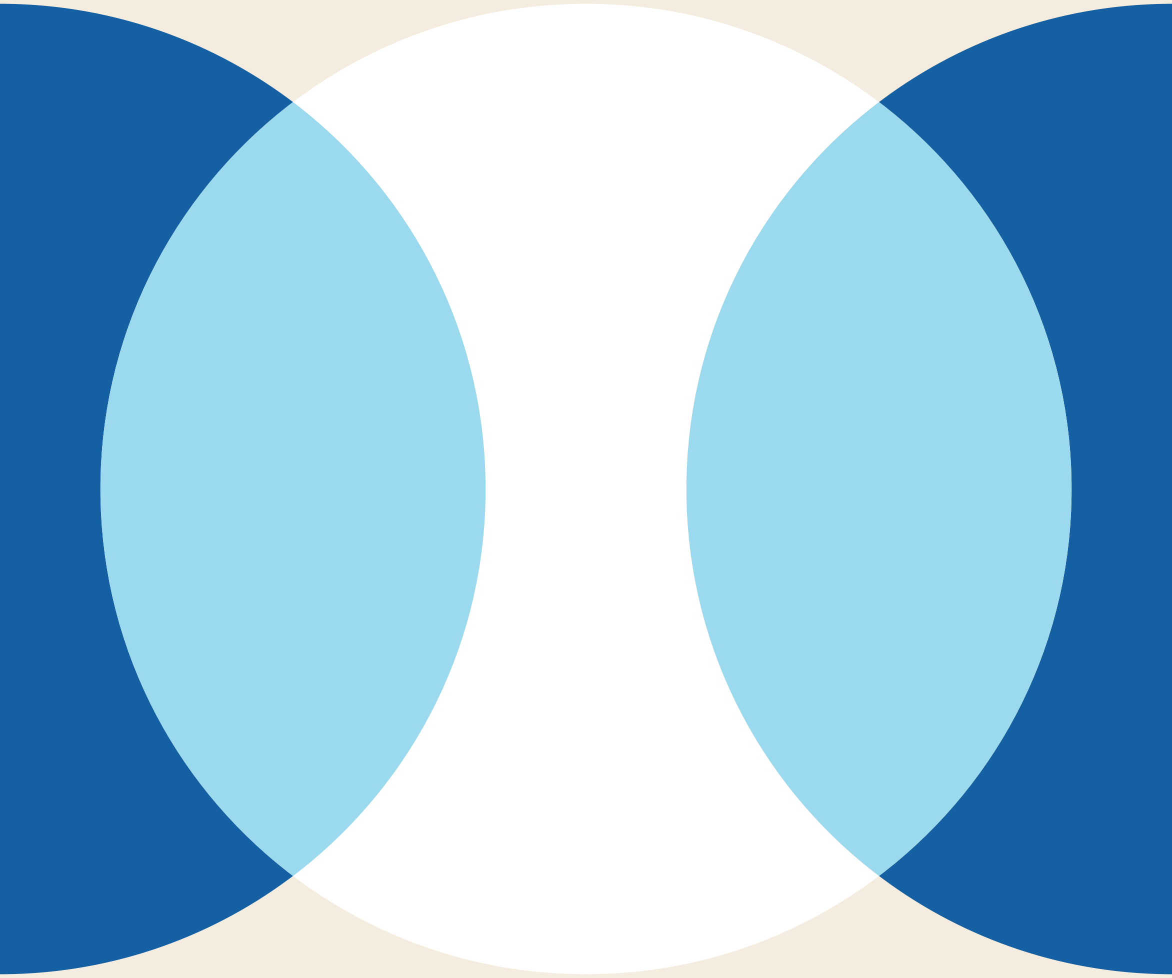
Connecting Neuroscience with Education

Critical Considerations

Donna Coch and David B. Daniel



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Connecting Neuroscience with Education: Critical Considerations

IBE Science of Learning and Teaching: Foundations for Curriculum and Teacher Development

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By

Donna Coch and David B. Daniel

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All chapters in this book have undergone peer review.

The Library of Congress Cataloging-in-Publication Data is available online at https://catalog.loc.gov

Typeface for the Latin, Greek, and Cyrillic scripts: “Brill”. See and download: brill.com/brill-typeface.

ISSN 2948-2208
ISBN 978-90-04-73529-3 (paperback)
ISBN 978-90-04-73530-9 (hardback)
ISBN 978-90-04-73531-6 (e-book)
DOI 10.1163/9789004735316

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Contents

UNESCO IBE Science of Learning and Teaching Series

The UNESCO International Bureau of Education (IBE) is leading efforts to transform curricula and pedagogy in service of more sustainable, just, and resilient futures. That vision has taken on new urgency. As the world contends with overlapping crises – from growing inequalities, democratic backsliding, increasing polarization of societies, and protracted violent conflict, to the climate crisis and the aftershocks of the Covid-19 pandemic – education systems face mounting pressure to adapt. At the same time, technological change is reshaping the world of work and human interaction, requiring education not just to respond to change, but to lead it.

In this context, the IBE has intensified its work to help rethink not only what learners need to know, but how education systems can actually support meaningful learning. This isn't about adjusting curricula or adding new content – it's about fundamentally reimagining teaching, learning, and assessment in line with current understanding of how learning happens.

At the heart of this effort lies a key question: How can we bridge the gap between what science tells us about learning and what happens in classrooms every day?

The answer is neither simple nor static. Scientific research, especially in neuroscience, offers powerful insights, but these are often misinterpreted, oversimplified, or lost in translation. Since 2016, the IBE has been working to close this gap. Through its science of learning knowledge brokerage initiative, it translates cutting-edge research into practical, credible knowledge that can inform policy, improve teaching, and enhance learning.

Over nearly a decade, the IBE has become a recognized global reference at the intersection of science and pedagogy. In partnership with the International Brain Research Organization (IBRO), it has cultivated a vibrant international community of researchers, educators, and policymakers committed to advancing evidence-informed practice.

The annual IBRO/IBE Science of Learning Fellowship, launched in 2016, has been central to this mission. Between 2016–2024, leading neuroscientists joined the IBE to communicate emerging research in ways that were both rigorous and relevant for those shaping education systems. Their insights were amplified through the IBE Science of Learning Portal and the blog IBE Speaks, both of which promoted stronger public understanding of how learning happens and why it matters.

Now, nearly a decade on, this bold initiative is gaining new momentum. The IBE's commitment to strengthening the scientific foundations of education has only intensified – with a focus on sustained partnerships, reflective practice, and shared learning across borders.

A key milestone in this effort has been the development of a new publication series: *IBE Science of Learning and Teaching: Foundations for Curriculum and Teacher Development*. This series was launched with the support of long-time IBE collaborators Donna Coch and David B. Daniel, two leading figures promoting the responsible translation of scientific findings to inform authentic educational practice.

The series makes a clear case: Educator models of learning should be informed by scientific evidence when possible and scientific findings should always be vetted for desired impact in their intended context before committing to them. Teacher preparation and professional development programs should prioritize scientific literacy – not as abstract knowledge, but as a fundamental tool for real-world teaching. When teachers understand how learning happens, they are better equipped to make it happen.

The first volume in the series, authored by Coch and Daniel, is both accessible and substantive. It explores how neuroscience can inform teaching and learning in meaningful ways, without falling into the trap of 'neuromyths'. From understanding research design and effect sizes to interpreting neuroscientific methods, it offers educators a practical, evidence-based guide to bringing research into the classroom.

Designed for teacher education and professional development, the publication balances depth with clarity. It includes recommended readings and a comprehensive review of the literature – making it a versatile resource for teacher training institutions looking to enhance their curricula.

While the science of learning has gained traction in some regions, the IBE's goal is to ensure its benefits are shared globally. This publication supports broader capacity-development efforts across UNESCO Member States by giving teachers tools they can trust – tools backed by scientific evidence, not just trends.

The IBE is immensely grateful to the authors for their generous, insightful, and rigorous contribution. Their work will help ensure that teachers around the world are not only better prepared, but also better supported to shape the futures of their students.

OVERVIEW

Using Scientific Evidence in Education

Pre-service and in-service teachers are bombarded with advice and information about how best to teach their students. For example, instructors in Education courses may tell you exactly which methods to use, social media posts feature beaming teachers declaring that their specific practices create brilliant students, and publishers and professional development gurus tout their programs and curricula and aggressively sell their products as the very best. Some may even claim that their products and approaches are "brain-based". Such advice about "what works" can be authoritative, coming from trusted sources and colleagues, or it can be based on apparent consensus among a subset of unknown practitioners, with many likes, up-votes, or retweets. But how can we really know if what these people claim works actually would support our students in their learning and development? One way is to appropriately seek out and consider scientific evidence that can help to determine whether such claims are valid.

1 What Is Scientific Literacy?

Using scientific evidence requires developing basic *scientific literacy*. Scientific literacy is "the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity" (National Research Council, 1996, p. 22). It includes, for example, an understanding of *control groups*. In education, a control group is a group of students who do not receive the intervention, are not exposed to the new teaching technique, or do not use the new product or curriculum. However, ideally, the control group still does something—just something different from the new strategy being tested. In contrast, the *experimental group* is a group of students who do receive the new intervention, are exposed to the new teaching technique, or do use the new product or curriculum. It is the comparison of the performance of the control and experimental groups that can provide evidence of what works. Not just a claim or an observation or a feeling that something has a positive effect on an outcome that is important to us (*believe me, this really works!*), but actual scientific evidence to confirm that it does (*the experimental group outperformed the control group by*

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10%). The existence of a control group, the composition of the control group in relation to the experimental group, what the control group is asked to do, and what outcome measures are considered are all important to determining what works. Understanding control groups is just one aspect of scientific literacy; other concepts such as *effect size*, *statistical and practical significance*, and *unintended adverse effects* are also important to know for using evidence in education.

When educators are keen to use neuroscience in their classrooms and educational products claim to be "brain-based", basic neuroscientific literacy is an additional requirement for determining what works. A colorful picture of an fMRI scan may be seductive (McCabe and Castel, 2008) but it does not tell you that "this is the part of the brain that does *X*". In reality, no part of the brain works in isolation. Understanding what such images do and do not depict (that is, understanding a little bit about the brain and neuroscience methods) can help teachers to not be misled and succumb to their allure. Further, neuroscientific evidence is often derived from studies that are not designed to directly address applications in the classroom. The inference from a study examining isolated neural changes in response to controlled stimuli presented in a laboratory to pedagogical practices in a real-life classroom is often unjustified and invalid. A finding or image from a neuroscience study does not tell you that you should teach in one way or another; it cannot, because neuroscience operates at different *levels of analysis* than behavior, which is the primary source of information that a teacher has available to them in a classroom.

2 Why Is (Neuro)scientific Literacy Important in Education?

Deciding to value the scientific method and adopting an evidence-based stance are fundamental to guidance on connecting neuroscience and education. Professionalism in teaching involves building a knowledge base on learning, development, and teaching that is based on quality, up-to-date research evidence (Kelleher and Whitman, 2017) as well as classroom expertise and understanding of student characteristics in context. Scientific literacy, and sometimes neuroscientific literacy, are necessary to critically consider and understand that evidence and identify promising findings for practice. Part of scientific literacy for teachers is being able to translate findings from the scientific and neuroscientific literature in critical, principled ways that make those findings usable knowledge for the classroom. Educators who have committed to an evidence-based approach to education and seek to responsibly leverage scientific findings to improve learning and teaching are scientifically literate as both consumers and producers of research evidence (Davies, 1999). Teacher preparation and professional learning programs must support the development of scientific literacy in educators if education is to become evidence-based, allowing us to determine “what works” in education in valid, reliable, and replicable ways.

CHAPTER 1

Using Research Evidence

Concepts Relevant to Educators

1 Introduction

Expert teachers have developed a vast knowledge base about learning, development, and teaching. Although teacher expertise takes different forms across time and cultures (Berliner, 2001), this typically includes content knowledge about the subjects they teach, pedagogical knowledge about the methods they use, pedagogical content knowledge about how to teach content so that students learn, curricular knowledge about sequences of instruction and expectations, knowledge about educational contexts, knowledge about educational goals and values, and knowledge about learning, learners, and their development (Beijaard and Verloop, 1996; Borko and Putnam, 1996; Cochran et al., 1993; Darling-Hammond and Bransford, 2005; Shulman, 1987).

Educators "construct their knowledge in dynamic and complex ways, incorporating and intertwining knowledge about student behavior and learning, subject-matter difficulty, multiple perspectives, and educational context into their pedagogy and thinking" (Wilke and Losh, 2012, p. 222). This integrated understanding across domains is fundamental to professional competence (Lehmann et al., 2020, p. 905). Teachers rely on this integrated knowledge in teaching and learning interactions every day, often moment to moment, in the ever-changing and complicated context of the classroom (Shulman, 2004).

1.1 *Teachers' Mental Models Inform Practice*

A teacher's knowledge base informs and interacts with their *mental models*, personal conceptions and beliefs about how and why things like learning, development, and teaching work (Carroll and Olson, 1987). Such models underlie and guide practice based on beliefs about the nature of children's minds and how to help children learn (Haim et al., 2004; Mevorach and Strauss, 2012; Olson and Bruner, 1996; Strauss, 1993). This kind of knowledge about learning can predict teachers' instructional behaviors (König et al., 2014; Lohse-Bossenz et al., 2015; Strauss, 1993). Teachers' beliefs about learning are related to their practices in numerous ways, such as by acting to filter information

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and experiences, framing situations and problems, and guiding intention and action (Fives and Buehl, 2012). For example, teachers whose models incorporate the (accurate) belief that teaching ability is learned are less inclined to learn a new pedagogical strategy without also understanding why and how it works (Fives and Buehl, 2014). Expert teachers are effective in part because they have developed integrated knowledge bases and models that comprise a deep understanding of how students learn and how teaching affects learning (Daniel and Chew, 2013).

1.1.1 Mental Models Are Resistant to Change

In teacher training, current and future educators are exposed to new information about learning, development, and teaching (Daniels and Shumow, 2003). Integrating new and existing information across different domains into a coherent understanding is a key element of teacher development (Lehmann et al., 2020). Some of the new information that teachers are exposed to may align with their existing models and is therefore more likely to be incorporated into practice. For example, anyone who works with children notices rather quickly that they are not all the same. Effective teachers observe these *individual differences* every day and are eager to adapt their practices to accommodate them. There are many theoretical classification systems that might appear to be helpful in this regard, such as left- or right-brain dominance (Kitchens et al., 1991), various learning styles (e.g., visual, auditory, or kinesthetic) (Fleming and Mills, 1992), or some interpretations of multiple intelligences theory (Gardner, 1999). These sorts of classification systems are often taught in teacher training programs and tend to be popular with educators because they resonate with mental models of individual differences in learners based on personal experiences (Aypay, 2009; Lethaby and Harries, 2016).

Although they may seem useful at first glance, such classification systems have not been demonstrated to be valid in the classroom (Beaumont et al., 1984). But when confronted with research data showing that students cannot be accurately categorized like this and that, for instance, “matching” teaching style with learning style (e.g., teaching a student purported to be a visual learner with a visual curriculum) does not increase (and often inhibits) student learning (Pashler et al., 2008), educators tend to be resistant to altering their views (Utter et al., 2018). Instead, they discount the new data and persist with the erroneous beliefs that they have already incorporated into their existing models (Utter et al., 2018); indeed, information that challenges existing models is more likely to be resisted, reflecting a process called *belief perseverance* (Chinn and Brewer, 1993; Savion, 2009). Existing mental models about children's learning and teaching may act to filter new and better information and may even take priority over subject matter knowledge (Strauss et al., 1998). In complementary efforts to reinforce their existing models, educators may even actively seek out further information that confirms faulty beliefs, typically online or from like-minded peers (Education Week Research Center, 2017), reflecting a process called *confirmation bias* (Nickerson, 1998). However, very clear disconfirming evidence may help people to shift their beliefs (Anglin, 2019), *if* they are willing to consider doing so.

Of course there are individual differences across learners—they just are not accurately or adequately captured by these categorical classification systems and teaching approaches need not "match" with such classifications for successful learning to occur. Thus, a more flexible model of individual differences and how such differences interact with learning and teaching practices, rather than a rigid one based on unsupported categorization systems, would be more productive. This underscores the importance of guiding educators in the development of accurate and usable models of both the learner and the role of the teacher in facilitating learning and development instead of focusing on a small set of "best practices" that may not be very well supported by research or applicable across contexts. Teacher educators could help teachers conceptualize learning as multiple processes (Thomas et al., 2019, pp. 479–480) that all students are capable of instead of categorizing students into learner types (Wilke and Losh, 2012, p. 235). Such a model could be informed by building a knowledge base of accurate, reliable research evidence regarding learning during teacher training rather than exposing new teachers to such classification systems.

1.1.2 Using the Scientific Method to Guide Change

There are many challenges involved in meaningfully integrating research evidence on learning, development, and teaching into educator training. Some of these challenges are disciplinary. For example, in *evidence-based practice* in medicine, research evidence, clinical expertise, and patient preferences and characteristics are all integrated to guide practice (Spring, 2007, p. 611). Unlike medicine, however, the field of education has yet to adopt a common standard of proof across the profession (Willingham and Daniel, 2021). The term *evidence-based* implies a specific endorsement of empiricism as a system of proof. In the discipline of education, this is the idea that education can be guided by the use of scientific methods and what those methods yield for effective policy and practice, integrated with classroom expertise and student characteristics. However, the education sector is generally lacking in "support [for] a culture or politics that prizes empiricism and learning" (Willingham and Rotherham, 2020, p. 71). Indeed, as a field, education has struggled for decades to build connections between empirical research and educational practice (Condliffe Lagemann, 2000; Shavelson and Towne, 2002). Despite a marked shift toward evidence-based practice in education in the 21st century (Coldwell et al., 2017; Davies, 1999; Hattie, 2009; OECD and CERI, 2007; Thomas and Pring, 2004), an evidence-informed ethos is not common in most schools and remains antithetical to education for some (Biesta, 2007; Biesta, 2010). Thus, using research in educational practice and policy can be difficult at many levels (Burns and Schuller, 2007; Farley-Ripple et al., 2018; Gore and Gitlin, 2004; Joram et al., 2020).

Notwithstanding the challenges, many countries and organizations have endorsed the scientific method as a standard of proof in education and made a commitment to promoting the use of empirical evidence to guide training, policy, and practice in education (Cooper et al., 2009; OECD and CERI, 2007). Some foundations, recognizing the *research-to-practice gap* in education—namely, that research evidence concerning how to improve education and learning exists but is not implemented (Carnine, 1997)—have funded global programs to address it (Master et al., 2021). At a local level, the most strongly research-engaged schools integrate research evidence as part of a widespread educational ideology and culture (Coldwell et al., 2017). Indeed, education is a cultural effort to guide development and the decision to use research evidence in education is ultimately based on cultural values (Sheridan et al., 2005).

1.2 *Integrating Research Evidence into Our Thinking about Teaching and Learning*

If it is decided that scientific and neuroscientific research evidence is of value in education, then teachers should receive support in integrating research evidence with both their clinical experiences in the classroom and student characteristics, in accordance with evidence-based practice (Spring, 2007). It might be expected that teachers, like other professionals (Neimeyer et al., 2012; Zaboski et al., 2017), will struggle with recognizing when and how to replace, amend, or enhance elements of their current models with those based in research evidence. Learners must overcome confirmation bias and belief perseverance to create marked shifts in their mental models, revising or replacing maladaptive understandings—a difficult and effortful process of *conceptual change* that involves complex interactions between cognition, motivation, and emotion in sociocultural context (Chi, 2008; McDevitt and Ormrod, 2008; Murphy, 2007; Nussbaum and Novick, 1982; Pintrich et al., 1993; Vosniadou, 2002). [This may remind you of the effortful process of *accommodation* in Piagetian theory, in which a child's current understanding must be revised to incorporate new, incompatible information (Piaget, 1952).] Growing from familiar, personal, experience-based models to updated, augmented, evidence-informed models of learning, development, and teaching through meaningful interaction with the research literature is a challenging and long-term process. For most teachers (Joram, 2007), a process of conceptual change is necessary to incorporate evidence from behavioral research studies into their models—and, perhaps even more so, evidence from neuroscience research specifically.

Using research evidence in teacher training goes beyond simple exposure to findings, principles, or practices derived from research; these can be incorporated or eschewed relatively easily, depending on existing mental models. The use of evidence includes a deeper consideration of the methods and processes used in the development of these findings, principles, and practices and involves wider acceptance of pedagogy as an applied science that can guide the processes of teaching and learning. It requires some level of development of scientific thinking, moving from simply using theories and being influenced by evidence to thinking about more complex interactions between theory and evidence (Kuhn, 1989). Fundamentally, it concerns supporting and engaging teachers in building an integrated, interdisciplinary knowledge base (rather than just a collection of facts or beliefs) with an ultimate goal of informing and refining mental models themselves (Wilke and Losh, 2012).

Hypothetically, for example, rather than memorizing a static list of "best practices", beginning teachers could consider the research evidence in order to build a knowledge base and toolbox of evidence-informed practices to use reflectively and flexibly with different students across different contexts—accompanied by underlying evidence-informed models of individual differences and learning as contextual and situated (Lave and Wenger, 1991). Through the perspective of research evidence, teachers entering the profession as well as those participating in professional development would not only learn what to do but would also better understand how, why, and when to do it. The conceptual change that we are advocating here is for models of learning, development, and teaching informed by a deeper understanding of how to use research evidence in critical, principled ways, supported through teacher training programs.

1.3 *Building Accurate and Evidence-Based Knowledge*

As a prerequisite, educationalists who are motivated to build an evidence-based knowledge base and commit to enriching their models of learning, development, and teaching must adopt the scientific method as a viable system of proof and become scientifically literate in order to gather the evidence and be able to use research and data in critical, principled ways (Mandinach and Gummer, 2011; Mandinach et al., 2015; Stanovich and Stanovich, 2003). That is, educators interested in using neuroscience research to inform teaching and learning must first understand relevant concepts in both research and neuroscience. Teachers “should at least have a familiarity with basic research principles and methods … district leaders would benefit from more experience and training in this arena as well” (Willingham and Rotherham, 2020, pp. 74–75). Understanding the nature of research provides a foundation for revising old and building new models that incorporate research evidence, along with classroom experiences and student characteristics, while promoting both the agency of teachers (Berliner, 2001) and the professionalism of teaching (Amirova et al., 2020; Demirkasımoğlu, 2010).

Using scientific evidence requires developing basic *scientific literacy*: “the knowledge and understanding of scientific concepts and processes required for personal decision making, participation in civic and cultural affairs, and economic productivity” (National Research Council, 1996, p. 22). In the following sections, we discuss some of the primary concepts needed to develop the scientific literacy necessary to evaluate research and to guide decision-making about whether that research is relevant and potentially useful in the classroom.

2 Types of Research Studies

If you will be spending time in the research literature, there are fundamental concepts that are useful to know when reading and evaluating research studies. The strength of the evidence in support of an intervention or educational practice or approach is determined in part by what kind of research study has been conducted: Strong evidence can come from *experimental studies*, moderate evidence from *quasi-experimental studies*, and promising evidence from *correlational studies* (US Department of Education, 2016).

2.1 *Experimental Studies*

Although not without controversy (Connolly et al., 2018; Cook and Gorard, 2007; Wiliam, 2022), the strongest experimental design is a *randomized controlled trial* (*RCT*). In this design, a group of students is split by random lot into a *control group*, which does not receive an intervention, and an *experimental group*, which does receive the intervention. In education, the intervention could be a new curriculum, program, or teaching technique or practice, for example. All the students are assessed on the outcome measures before the intervention has begun (called the *pre-test*) and after it has ended (called the *post-test*). This is illustrated, in simplified form, in Figure 1.

When a large number of students is involved and students are assigned to groups appropriately, there are usually no differences in scores on the outcome measures between the two groups at pre-test (because of the random

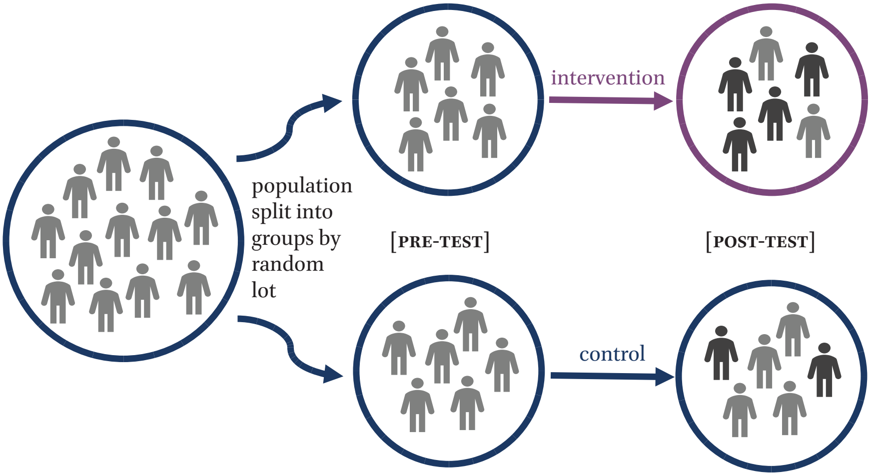

FIGURE 1 An illustration of the RCT design with random assignment to intervention and control groups and a pre-test and post-test comparing the two groups on the outcome measure(s)

assignment of students to the control and experimental groups). Thus, if there are differences in scores on the outcome measures between the two groups at post-test (e.g., four students in the experimental intervention group showed improved scores at post-test, but only two students in the control group did in the illustration in Figure 1), we can make a *causal* interpretation: that any differences in outcomes between the two groups were *due to* (that is, caused by) the intervention. When a large number of students is involved across multiple schools and multiple settings (for example, in urban, rural, wealthy, and poor districts in many countries), we can further *generalize* the findings beyond just the students directly involved in the study to students like them who were not part of the study. That is, we can infer that we would see similar results in the wider population of similar students.

The *p value* or *significance value* allows us to make such inferences. It indicates whether a finding is more or less likely to be due to chance. By convention in the social sciences, $p = .05$ is the cut-off for statistical significance. If the value of the p statistic is less than .05, then we say that the difference between the two groups for that outcome measure was significant and we can go on to consider how to use the finding. But if the value of the p statistic is greater than .05, then we say that the difference between the two groups for an outcome measure was not significant and we do not discuss the result further or put the finding to use. This is problematic in education because *statistical significance* (as represented by the p value) and *practical significance* are not the same thing, a concept to which we will return.

We can also characterize a difference between the two groups for an outcome measure in terms of *effect size* (also known as *Cohen's d* or just *d*). The effect size is the size of the difference between the two groups, put into a standardized scale. The standardized scale allows us to compare across different measures. For example, if one outcome measure had a score range from 0 to 10 and the difference between the control and experimental groups at post-test was 2 points and another outcome measure had a score range from 200 to 800 and the difference between the groups at post-test was 43 points, for which outcome measure did the intervention have a greater effect? Calculating the effect sizes will tell us. The concept of standardized effect sizes is not very intuitive. To better highlight the practical importance of the size of the differences between groups, percentile gains might be used as a substitute for effect sizes (Baird and Pane, 2019).

It is important to remember that the effect-size statistic represents the size of the effect in the *overall* comparison of the two groups or interventions at post-test. But the overall effect size may not apply to subgroups of participants in the study. For example, in meta-analyses (studies that calculate an overarching effect size based on the effect sizes reported in multiple previous studies), the average overarching effect size associated with teaching a *growth mindset* (the belief that intelligence can change with effort) was small (Sarrasin et al., 2018; Sisk et al., 2018). But the average overarching effect size can hide patterns across subgroups of participants: Growth mindset interventions had negative effects (poorer, rather than better, scores after intervention) for some students

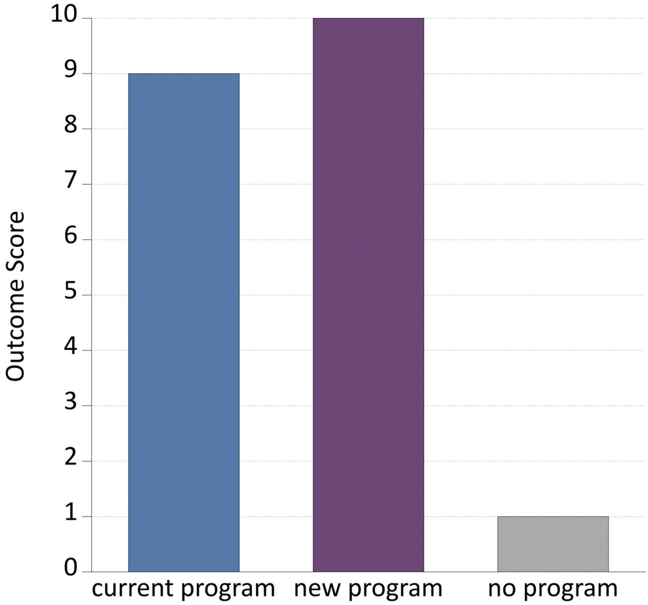

FIGURE 2 Hypothetical data illustrating the importance of the nature of the comparison control group

in some studies but were associated with markedly better effects for at-risk students and children from under-resourced backgrounds in some studies (Sarrasin et al., 2018; Sisk et al., 2018). *Statistically*, in terms of effect size, the overall findings from the meta-analyses are underwhelming. But, *practically*, for some subgroups of children, the findings might have some limited utility.

The issue of practicality is important in other ways, as well, for educators who want to use research in their practice. Effect sizes may hint at a considerable difference in post-test scores between the experimental and control groups, but the implementation of the strategy or intervention described in the research study may not be practical, or even possible, in the context of a particular classroom. For example, implementing the strategy may require more time or resources than the teacher has available, especially in the context of a dynamic classroom with multiple learning objectives and subjects. Indeed, to be effective, the strategy or intervention must mesh well with the other subjects being taught and the culture of the classroom as well as work within the broader contexts of the school and community. These judgments of practicality are essential, but often require information that is not included in a single research study. Often, it is the educator's responsibility to weigh them.

Turning back to the design of RCTs, the nature of the control group is particularly important in experimental studies. As in Figure 2, if the control group receives no instructional program while the experimental group receives the new intervention program, it is more likely that there will be a larger difference between groups (compare the gray and purple bars). But if the control group receives the best instruction currently available while the experimental group receives the new intervention, there might be less of a difference between groups (compare the blue and purple bars in Figure 2). In the first case, the new intervention program works better than nothing, which is hardly inspiring; indeed, this is "quite literally the weakest bar of comparison possible" (Sakaluk et al., 2021, para. 9). In the second case, the new intervention program works at least as well as the best program currently in use, which *is* inspiring: Now we have two programs that work well to choose from to use with our students. Thus, an effect size may seem impressive for a specific comparison, but studies do not typically include the key comparisons to the next best alternative or an active control group; better alternatives may exist that are just not considered in a particular study (Willingham and Daniel, 2021).

Also note that this provides another example of how statistics (in this case, p values) can be misleading in education. It may be the case that the difference in outcome scores between children who received the current program and the new program (the blue and purple bars in Figure 2) is not statistically significant (the p value in comparing the outcome scores of the two groups is greater than .05), but, despite the lack of *statistical significance*, that finding is certainly *practically significant* in this case (we have two programs that work about equally well). That is, here, the lack of a statistically significant difference (which would typically mean the end of discussion about the finding and its utility) has positive practical importance that should be discussed.

In addition, you will want to be aware of potential effects of novelty when evaluating research studies. If the experimental group does something wildly different than what students or teachers have typically done before (e.g., bouncing on exercise balls during math lessons in the hope of improving math achievement scores) and the control group continues to do what they have always done, any difference between groups may be due less to the intervention itself than to the excitement of doing something so new and different. Any initial positive effects of novelty may diminish over time for both student and teacher.

Finally, in evaluating RCTs, it is important to consider not only the intended effects but also the unintended adverse effects of intervention (Zhao, 2017). Whereas bodies like the Food and Drug Administration in the United States evaluate both safety and efficacy for medications, medical devices, and vaccines, there are no government bodies that similarly judge psychological treatments (Sakaluk et al., 2021, para. 14; Williams et al., 2021) or educational interventions. Although an educational intervention might "work" overall, according to statistics like the *p* value and effect size, it might also have harmful side effects. For example, an intervention might significantly raise scores on a standardized reading test but also make children hate reading (Zhao, 2017). This is an example of *unproductive success* in learning (Kapur, 2016). Motivation to read is associated with both breadth and depth of reading (Wigfield and Guthrie, 1997), which in turn has positive cognitive consequences well beyond reading (Cunningham and Stanovich, 1998). Are current higher test scores worth the trade-off of future unmotivated readers who never willingly pick up a book again? In this hypothetical case, future iterations of the intervention would need to involve a risk-benefit analysis and incorporate (and rigorously test) ways to minimize the risks.

Despite the challenges of conducting RCTs in educational settings (Illingworth et al., 2019), over 1,000 reports of RCTs in education were published (in English) internationally between 1980 and 2016 (Connolly et al., 2018).

2.2 *Quasi-Experimental Studies*

A quasi-experimental study is like an experimental study (an RCT)—but, crucially, without the random assignment of students to the control group and the experimental group. Random assignment to groups helps to ensure that there are minimal differences between groups at pre-test, which allows for causal interpretations of post-test results. However, sometimes random assignment to groups is not possible. For example, if the intervention involved some sort of whole-class instruction, it might be difficult to teach to the experimental half of the class and send the control half of the class away during that time. In this case, perhaps each classroom (rather than each student) might be assigned to either the control or experimental condition. With quasi-experimental studies, we are less certain about causality because differences at pre-test (for example, individual differences in both students' background knowledge and classroom teachers' skills) are not controlled for.

As with experimental (RCT) studies, quasi-experimental studies make comparisons between a control group and an experimental group; thus, all of the points regarding intervention and comparison groups also apply to quasi-experimental studies. It is also important to recognize, once again, that such comparisons (whether in experimental or quasi-experimental studies) involve individual students but are statistically based on averages across the students in each group. Figure 3 illustrates some of the issues that can arise in such comparisons. The group averages for Group A and Group B are indicated by the dashed lines and are statistically significantly different from one another (the *p* value in comparing the average of Group A scores to the average of Group B scores is less than .05). Thus, we can say that Group A scored higher than Group B. This means that, on average, individuals in Group A scored higher than individuals in Group B—not that each individual in Group A scored higher than each individual in Group B. The dots represent individual students within each group (an illustration of the concept of individual differences). With the exception of the two lowest scorers in Group B and the highest scorer in Group A, the score of any individual student could put them in either Group A or Group B. Thus, group analyses in many research studies may not capture the individual differences that teachers are interested in. However, developmental

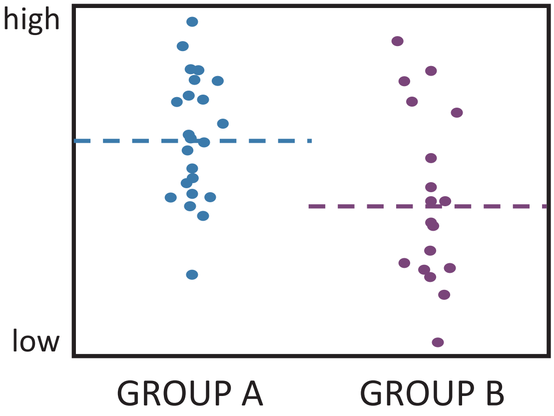

FIGURE 3 A dataset illustrating group (dashed lines are group averages) and individual (dots are individuals) differences

science may be moving toward new methods of data collection and analysis that "generate evidence applicable at the individual level" (Lerner et al., 2019, p. 306).

2.3 *Correlational Studies*

Correlational studies do not have a control group and an experimental group because they are not experiments and do not involve interventions. Rather, correlational studies involve observation and description. As the name suggests, correlational studies measure the relationships between variables (e.g., shoe size and height). The statistic called the *correlation coefficient* (or *Pearson's r* or just *r*) reflects both the kind and strength of the relationship between variables. Correlational studies do not provide any information about causality (that is, we cannot say that *because* a child wears larger shoes, they are taller or *because* a child is taller, they wear larger shoes). Further, correlational studies are plagued by the *third variable problem:* Two variables that seem to be related to one another may be related only through a third variable, not directly. In our hypothetical example, *age* seems a likely third variable (older children tend to be taller and older children tend to wear larger shoes).

Many of the things that might interest us in development must be investigated with correlational studies. For example, we might be interested in the effects of poverty on learning. Clearly, we cannot ethically assign one child to an "under-resourced" group and another child to a "well-resourced" group. But we can observe, describe, and measure what we see in children who are already growing up in under-resourced communities in comparison to children who are already growing up in well-resourced communities, being careful to control for possible third variables and not make causal conclusions.

3 Other Factors to Consider in Research Design

In addition to the type of research study (and its strengths and limitations), it is important to consider other contextual factors in critically evaluating research for use in education. For example:

- How the study might inform education. What is the main idea relevant to educators in the study? Not all studies of learning, development, and teaching are relevant to all educators, and some studies are not relevant to any.
- Whether the study addresses an important issue for you. For example, could the findings help to solve a problem that you have in your classroom, school, district, or nation? How might the research findings help you to be a better teacher?

- The implications for practice. Whereas some research evidence is best used to enhance your learning and development knowledge base, other research findings may have implications for practice. If there are implications for practice, were they tested or merely implied? If tested, were they tested in a context similar to the one in which you will use the practice?
- The cost of the intervention and the availability of funding. Even if a study using an RCT design reports significant findings and large effect sizes, if the cost of the intervention used in the study is prohibitive, the results may not be useful to you.
- The cost of the intervention in terms of time. If a study required an entire school year and many hours of teacher and administrator time, you may decide—even if the results are impressive—that the intervention is not worth the time commitment for your school or district or country. Consider the cost both in terms of administrator, teacher, and student time and in the context of trade-offs with other subjects and activities.
- The number of research participants and the population from which they were drawn. If there were few participants and their demographics do not reflect those of your students and your local culture, there is less reason to assume that the intervention will work similarly (or the results will be similar) with your students.
- The setting for the study. If you want to use the evidence in your school, it is more likely that you will obtain similar results if the setting of the study is like your school (e.g., primary or secondary, public or private). If the study was conducted in a laboratory, it cannot be assumed that similar results will occur in a classroom.
- The training and resources needed. If the people in the study administering the intervention were highly trained research assistants using specialized materials, it cannot be assumed that if teachers in your school administer the intervention without training and without access to the same materials the same results will be found.
- The nature of the outcome measures. There are many factors to consider here, such as who administered and scored the pre-test and post-test measures and whether they could have been biased. In addition, were the outcome measures standardized tests or were they designed by the researchers or teachers involved (in which case the findings may be less reliable)? Further, were multiple and varied outcome measures used that could address unintended adverse effects?
- The concordance of the intervention, strategy, or approach of the research study with your cultural contexts. If what the researchers did cannot work in harmony within the sociocultural contexts of your classroom, your school,

your community, or your national educational policies, it is unlikely that the research findings will be of use to you.
- Other factors that could affect the impact of the researched techniques in your classroom. For example, teachers' experience, motivation, and enthusiasm, and students' prior levels of knowledge, emotional states, and motivation (Perry et al., 2021, p. 13).

4 Types of Publications and Sources of Information

When using research evidence in education, the strongest source consists of peer-reviewed articles published in scholarly journals. Many of the careful approaches and the critical analysis used in peer-reviewing an article are similar to the skillset needed to read a research article in order to use its findings. Although not foolproof, peer review before publication in a professional journal helps to ensure the quality and integrity of the research reported in an article (Gastel, 2002; Seals and Tanaka, 2000).

Primary source research articles report new findings for the first time or replicate previous findings. Replication is key to science and evidence is more dependable when it is consistent across multiple studies than if only a single study has reported a given finding (Baker, 2015; Wiliam, 2022). *Systematic reviews* and *review articles* summarize across primary source research articles and can provide an overview of a subfield as well as highlighting trends and patterns in the research findings beyond a single study; thus, they may be particularly useful to educators interested in using research evidence. As noted above, *meta-analyses* re-analyze data from multiple primary source articles in order to calculate an overarching effect size across studies and come to new conclusions based on existing data. Therefore, they also provide a kind of summary across studies. But a meta-analysis can be only as strong as the weakest contributing primary source article included in its analysis (Slavin, 2017). Other sorts of articles may be found in scholarly journals, as well; for example, commentaries, opinion pieces, conference proceedings, responses, and letters to the editor. These are less dependable sources of evidence without additional supporting research.

Unfortunately, although they may be interested in using research evidence, some studies suggest that educators do not tend to engage with professional research literature (Landrum et al., 2002; Williams and Coles, 2007). For example, in a survey study of 312 teachers and 78 head teachers in the United Kingdom, the authors found that respondents were "positively motivated towards the use of research evidence, [but] their actual use of information from research was limited" (Williams and Coles, 2007, p. 185). In another survey study of 127 teachers in the United States, respondents rated other teachers and colleagues, workshop/conference presentations, college courses, and professional journals as sources of information (Landrum et al., 2002). Professional journals were rated as significantly less trustworthy than information from other teachers or conferences/workshops and information from fellow teachers was rated as significantly more usable and accessible than information from college courses or professional journals (Landrum et al., 2002). Trustworthiness involves the confidence that a practitioner has in the research findings, usability concerns the practicality of a research-based practice when attempted to be put into use, and accessibility is the extent to which the research findings are available to those who want to use them; each plays an important role in the potential to bridge the research-to-practice gap (Carnine, 1997, p. 514). That teachers in this study found information from fellow teachers more trustworthy, usable, and accessible than information from peer-reviewed journals is problematic if our goal is to pursue evidence-based practices.

There are also, of course, many other kinds of publications beyond scholarly and professional journals. For example, dissertations, completed as part of graduation requirements for doctoral degrees, can involve research. However, this research has not yet been peer-reviewed or published; rather than using the dissertation as a source, look for the primary-source, peer-reviewed article version of it (if none exists, the research may not yet be strong enough to publish). There are also all sorts of reports, white papers, and guidelines from various agencies and individuals. Again, most of these are not peer-reviewed, and they are often developed with specific agendas in mind. Further, it is important to consider who funded the research reported and whether there may be any possible bias or conflicts of interest that strongly indicate caution is advisable in using the findings. In addition, there are secondary sources such as trade books. For example, a plethora of such books claims to reveal "brain-friendly", "brain-based", or "brain-compatible" teaching methods. These, too, are not peer-reviewed and the credentials of the authors (in both neuroscience and education) should be carefully considered, particularly if the book is trying to sell a program or curriculum (Alferink and Farmer-Dougan, 2010). All teaching and learning involves the brain; whether the teaching is cringe-inducing or awe-inspiring, learning happens in the brain (which is, of course, situated in a body and a wider context).

When relying on such secondary summaries of primary sources (that is, second-hand knowledge), it can be easy to be influenced by things like scientific-looking reference styles and credentialed author names (Zaboski and Therriault, 2019). While where the information fits within the scientific literature and who the source of the information is are important, details of the study design, methods, and findings are more important. For example, the results of a large, well-designed RCT are potentially far more practically useful than the findings from a small survey study. Familiarity with the language and methods of scientific and neuroscientific research "allows teachers to distinguish academically rigorous content from conjecture" (Amiel and Tan, 2019, p. 2). Many fields beyond education are plagued by pseudoscientific claims and the "warning signs" are similar across disciplines: For instance, pseudoscientific claims are espoused by authors who continually emphasize confirmation and ignore contradictory evidence, evade scientific peer review, over-rely on testimonials and anecdotal reports, make extraordinary claims, and fail to acknowledge any boundary conditions (claiming rather, for example, that their ideas apply to all students of all ages under all conditions, Lilienfeld et al., 2012, pp. 22–28).

Finally, online outlets, including social media, are increasingly a source of information for teachers (Education Week Research Center, 2017). The quality of online sources is extremely uneven and thus the information they provide should be approached with caution. All of the caveats noted above regarding lack of peer review, bias, and lack of author credibility should be attended to when attempting to use internet sources to build knowledge or guide practice. It is particularly important to recognize that the fact (or illusion) that something is popular does not make it correct or even useful. Thus, a skeptical, curious, critical, and informed perspective should be deployed across all sources of information. No matter where you encounter information to guide practice, that information is merely a hypothesis for your own teaching context and must be carefully examined and considered (e.g., in terms of potential adverse effects and practical utility) before being tested as a possible addition to your teaching repertoire.

One survey on sources of information in education asked over 500 K–12 teachers in the United States where they had learned about education trends or new ideas worth pursuing in their classrooms (Education Week Research Center, 2017). Seventy-eight percent marked professional development opportunities, 71% marked colleagues/word of mouth, 50% marked teacher-focused websites, 40% marked social media, and only 26% marked research journals (Education Week Research Center, 2017). Thus, not much seems to have changed since focus group data from the early 1990s suggested that teachers' "biggest source of information was the teacher down the hall", prompting the interviewer to quip "it's hard to conceive of somebody going through law school or medical school or becoming a [certified public accountant] without really understanding and having it drummed into them, how to get the most current information" (Kaestle, 1993, p. 27). Valuing having up-to-date research and situating practices informed by this research "at the core of what you do … is what it means to be a professional" (Kelleher and Whitman, 2017, para. 5).

Indeed, making current research available and accessible to educators and training them to find, use, share, create, and manage knowledge is integral to educators' building a research-informed knowledge base (Leask and Younie, 2013; Mandinach et al., 2015; Warby et al., 1999). Teachers' beliefs that research is not practical, contextual, credible, or accessible (Gore and Gitlin, 2004, p. 35) may have merit, especially without supportive training from an empirical perspective in how to critically consume research. Surely, providing educators access to primary source research literature and developing the scientific literacy skills to consume it critically are not easy and would require fundamental changes in teacher education (Leask and Younie, 2013; Mandinach et al., 2015). But teachers who can translate their problems of practice into questions that are addressed in the research literature and then read that literature for relevance (e.g., in terms of context), inference (e.g., in terms of research design), impact (e.g., in terms of effect size), and importance (e.g., both statistical and practical) (Gordon and Conaway, 2021) are well on their way to both addressing their own questions and constructing evidence-informed models.

Access to research and the skills to critically evaluate it give teachers the agency to discover answers to their pedagogical questions, pose new queries, and augment their knowledge bases and models of learning and teaching with research evidence. Thus, "the ability to seek out, critically evaluate and integrate appropriate evidence from research is recognized as an important aspect of development and innovation in professional practice" and "its importance in critical reflection and decision-making, and engagement in creating and effecting change, is recognized in evidence-based practice initiatives" (Williams and Coles, 2007, p. 186). Educators might see research as providing direction, provoking thinking, or adding value to their practice (Cain, 2016). None of these uses of research need undermine a teacher's democratic and liberal values, as these can coexist (Cain, 2016). As educators become more familiar with the research literature, perhaps the research-to-practice gap (Broekkamp and van Hout-Wolters, 2008; Carnine, 1997) will narrow. But this process may also highlight "a practice-to-research gap: Much of what teachers do in classrooms has never been studied empirically, particularly with neuroscience methods" (Coch and Ansari, 2012, p. 42).

CHAPTER 2

Using Neuroscience Research Evidence

Concepts Relevant to Educators

Beyond general aspects of research design and basic research concepts, educators seeking to build an evidence-informed knowledge base about learning, development, and teaching that includes evidence from neuroscience research will need more specialized knowledge. Such knowledge goes beyond general, summative claims such as teachers are “designers of experiences that ultimately change students’ brains” (Dubinsky et al., 2013, p. 318) (they are, but every experience changes the brain and most teachers in most classrooms will never directly observe neural changes in their students—although they may notice associated behavioral changes). If you will be spending time in the neuroscience research literature, there are some fundamental concepts that are useful to know when reading and evaluating neuroscience studies.

1 Neurons

A *neuron* is a type of brain cell that processes information (see Figure 4). Neurons process information through electrical and chemical signals. The electrical signals can be recorded noninvasively at the scalp using a method called *electroencephalography* (*EEG*). Another method that is closely related, *event-related potentials* (*ERPs*), involves recording the neural electrical activity related to processing a specific type of information. We will return to both of these methods.

In order to be active and process information, neurons need energy. That energy comes from oxygen and glucose. Neurons get oxygen and glucose from blood carried by blood vessels throughout the brain. Neurons that are more active need more energy. It follows that brain areas in which the bloodstream has less oxygen and glucose are areas in which the neurons are most active (because the neurons have used up the oxygen and glucose from the blood to be active). Methods such as *functional magnetic resonance imaging* (*fMRI*) provide a measure of relative oxygen levels in the blood. We will return to this method as well.

Sometimes when people talk about using neuroscience research in education, they mean using a scientific understanding of how the brain functions

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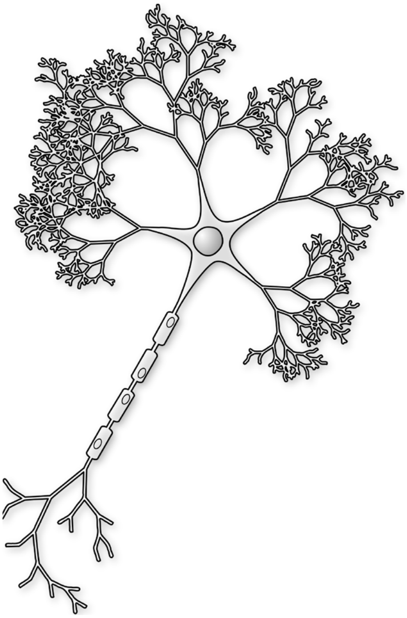

FIGURE 4
A schematic neuron, with the axon at the lower left (Source: Nicolas Rougier, https://commons.wikimedia.org/wiki/File:Neuron-figure-notext.svg, CC BY-SA 3.0)

at the cellular level (that is, at the level of the neuron) to inform educational practice. For example, we know from studies with rats and mice that neurons that are consistently active at the same time tend to form networks with one another (this is the concept of *synaptic plasticity*—*a synapse* is a space through which neurons communicate with each other). Sometimes the phrase neurons "that fire together wire together" (Schatz, 1992, p. 64) is used to describe this phenomenon. Repetition tends to strengthen such networks and stabilize learning. But note that this neuroscience research with nonhuman animals is not research about children learning and certainly not research about children learning in a classroom. It does not tell us what or how to teach or account for the background knowledge or motivation of the learner, nor does it indicate how much practice or repetition is required to help students in our classrooms form neural networks for different types of information (if that is even one of our goals in education).

Indeed, it has been noted that "the causal chain of reasoning from a basic neuroscience fact to a teaching method is often weak or nonexistent" (Coch, 2018, p. 311). Cellular neuroscience studies purportedly showing that "the brain learns this way" are not the same as classroom studies showing that "you should teach this way"; in fact, they are not studies of teaching at all. A great inferential leap is required to draw pedagogical conclusions based on the findings from such basic neuroscience research, which is not the same as evidence-based practice. Nevertheless, it is useful to know a little bit about neurons in order to understand the neuroscience *methods* that are used to study the developing human brain, as discussed below.

2 Levels of Analysis Issues

Another way of thinking about using neuroscience research in education involves a different *level of analysis* (see Figure 5). Rather than focus on how

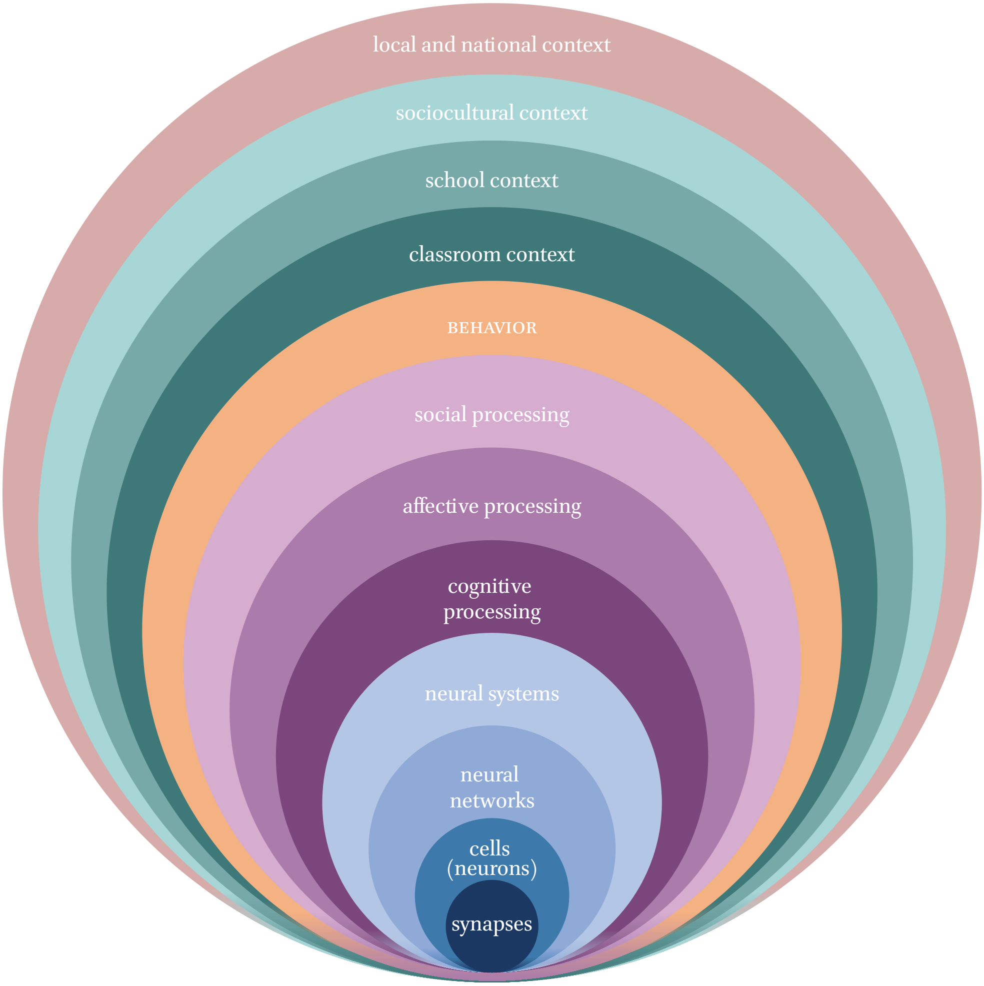

FIGURE 5 An illustration of the idea of levels of analysis. Basic neural levels (in blues) are not observable. Types of neural processing (in purples) are not observable but are inferable through behavior. Behavior (in orange) is observable and is the key level of analysis in classrooms. The wider contexts within which behaviors and social, affective, cognitive, and neural processing occur (in greens) are designed and constructed, as is the local and national context (in salmon), for example, in terms of educational policies.

neurons and synapses function based on rodent models, we could focus on neuroscience research that characterizes how the human brain changes across development and with learning, both inside and outside the classroom context (Bowers, 2016). We could focus, for example, on how neuroscience studies of various aspects of cognition, affect, and social processing in children and adolescents inform our understanding of learning and development in the "whole child"; in combination with other types of research findings (e.g., from studies of behavior), such neuroscience findings better reflect the interdisciplinary complexity of human learning and development (Cantor et al., 2019; Immordino-Yang et al., 2019; Osher et al., 2020). The integration of neural data with behavioral data on cognitive, affective, and social learning and development, each both informing and constraining the other, may be crucial to responsibly using neuroscience research in education. Such an interdisciplinary, scientific understanding and research-based knowledge base about how children learn and develop, in combination with classroom experience and knowledge of behavior in the classroom (that is, clinical experience and knowledge about student characteristics in an evidence-based practice model), can be part of the integrated understanding across domains that underlies teacher competence (Lehmann et al., 2020) and informs our complex models of learning and development, affecting our educational decisions (Darling-Hammond et al., 2020; Shelton, 2019).

From this perspective, neuroscience research operates at a different level of analysis (systems, rather than cells) and many neuroscience studies, rather than providing general information about "how the brain learns", can provide more specific information about how a child with a developing human brain learns certain skills and concepts (e.g., in the cognitive, affective, and social domains). However, this neuroscience research, too, is often not directly related to specific pedagogical practices (that is, the research design involves a manipulation of learning but not teaching). A science of learning and a science of teaching, although both necessarily interdisciplinary and intimately related, are not the same thing (Daniel and De Bruyckere, 2021; Mayer, 2018). It seems unlikely that neuroscience research would contribute in the same way or equally meaningfully to both.

A levels-of-analysis framework highlights at least two important hindrances to integrating neuroscience research findings into education-related knowledge bases and mental models. First, educationalists are concerned with many things that neuroscience research simply does not currently directly address, like attendance policies, grading rubrics, gradual release of responsibility, and community engagement. These factors are at entirely different levels of analysis than the ones at which neuroscience operates (refer to Figure 5). This has been called the *goals problem* in discussions about neuroscience and education (some "goals for schooling include problems that are outside of neuroscience's purview") (Willingham, 2009, pp. 544–545). Second, neuroscientists tend to study a single factor in isolation (e.g., selective attention or working memory). In contrast, educators are interested in the entire mind of a child in the context of the classroom, the school, the sociocultural community, and local and national education policies and priorities (refer to Figure 5). This has been called the *vertical problem* in discussions about neuroscience and education (Willingham, 2009).

These problems underscore the importance of recognizing that neuroscience findings can likely only make modest contributions to education—and must do so in principled ways. Neuroscience research cannot tell educators what to do: It is descriptive rather than prescriptive (Christodoulou and Gaab, 2009). Neuroscience studies alone cannot account for the complexity of either the classroom, learning and development, or teacher-student interactions in context. Rather, as educators construct their knowledge in complex ways, the integrated understanding across multiple perspectives that underlies expertise (Lehmann et al., 2020, p. 905; Wilke and Losh, 2012, p. 222) may be informed—at limited levels of analysis—by the perspective of neuroscience. As illustrated in Figure 5, neurobiological factors are but one of many influences on learning and development and they both mediate and are mediated by other factors at different levels of analysis.

In order to better understand neuroscience research evidence from studies with children and adolescents and how it might be integrated across different (limited) levels of analysis, it is important to first understand the neuroscience methods used in the research studies that generate the evidence. At the same time as this methodological knowledge is built, it is important to remember that neuroscience represents just one small piece of the breathtaking complexity of learning and development (Cantor et al., 2019; Osher et al., 2020) and provides just one of many possible kinds of interdisciplinary evidence that might be incorporated into our knowledge base to inform models of learning, development, and teaching.

3 Select Human Developmental Neuroscience Methods: How They Work

3.1 *Magnetic Resonance Imaging* (*MRI*)

MRI machines are used to create the structural images that are the result of an MRI scan (see Figure 6). An MRI machine creates a strong and uniform magnetic field. The strength of the magnetic field is measured in Tesla (T). A 3T MRI machine is stronger than a 1.5T MRI machine. The stronger the magnet,

FIGURE 6 An MRI machine (Source: National Institute of Mental Health, National Institutes of Health, US Department of Health and Human Services, https://commons.wikimedia.org/wiki/File:MRI_machine_with_patient_(23423505123).jpg, public domain)

the more detailed the structural images. In MRI recording, harmless radio frequency waves are sent through the magnetic field in pulses. Certain atoms (e.g., hydrogen atoms, such as those found in water and fat in the human body) absorb the radio frequency energy and, as a result, change their spin. A *radio frequency coil* in the MRI machine detects the change in spin and how the atoms *relax* back to their original spin once the radio frequency pulse is turned off. The resulting structural images are based on this spin and relaxation information (see Figure 7).

Although structural neural data can be useful, it is crucially important not to infer function based on structure (Bruer, 2002). For example, researchers have reported that adolescents who recalled experiencing severe stress in early childhood had smaller hippocampal volumes, as measured by MRI scans, than those who recalled having less stress in early childhood (Humphreys et al., 2019). The hippocampus is a brain structure deep within each temporal lobe, one in the left hemisphere and one in the right hemisphere. Functionally, the hippocampus is involved in learning and memory processes (Eichenbaum, 2004). Given the function of the hippocampus, this structural difference (smaller size in the more stressed group) seems like a potentially concerning finding. However, the researchers did not report any functional neural data in this study, nor did they report any behavioral data. So, we do not know if

FIGURE 7 A structural MRI scan of a human brain (Source: DrOONeil, https://commons.wikimedia.org/wiki/File:FMRI_Brain_Scan.jpg, CC BY-SA 3.0)

the size of the hippocampus was associated with poorer memory or learning as measured by behavioral or educational tasks, and we do not know if the smaller hippocampi functioned differently when processing information (as compared to adolescents with larger hippocampi). All we know is that these specific structures in the brains of these adolescents were smaller in size, on average, in this study; to go beyond that basic finding, given the data from this study alone, is scientifically invalid.

In addition, this was a *retrospective study* in which the adolescents (and their parents) were asked to recall previous stressful life experiences in early childhood, but these recollections were elicited and the MRI scans of the hippocampi were taken years later when the participants were adolescents. Thus, because of its design, this study can provide only an association (a correlation) between hippocampal size and stressful early life experiences—not a causal connection. That is, based on these data alone, we cannot say that more severe early life stress *caused* smaller hippocampal volumes in these adolescents. Similarly, we cannot say that these adolescents had smaller hippocampi as children, which *caused* them to experience more stress. The evidence suggests only an association; we can neither draw causal conclusions nor assume the nature of the association nor rule out the influence of a third variable.

3.2 *Diffusion Tensor Imaging* (*DTI*)

DTI is an MRI technique that focuses on structural fiber tracts in the brain (Le Bihan et al., 2001). These fiber tracts are the axons of neurons (refer to Figure 4), which are referred to as the *white matter* of the brain. They are called white matter because they are wrapped with a whitish, fatty substance called *myelin* (which is actually a type of glial cell called an *oligodendrocyte*). Axons that are wrapped with myelin—*myelinated* axons—conduct electrical signals more quickly and efficiently than unmyelinated axons. In addition, water molecules tend to move (*diffuse*) along the direction of myelinated axons rather than across them (this directional diffusion of water molecules is called *anisotropy*). You can observe a similar effect if you put the end of a piece of string into a cup of water: The water moves up along the string, not across it. DTI provides a measure of anisotropy, and thus a way to chart myelinated fiber tracts in the brain. That is, this method provides a kind of map of how neuronal axons reach out to make synaptic connections with other neurons across short and long distances in the brain and thus create neural networks. In DTI images (see Figure 8), the fiber tracts are color-coded according to conventions related to their orientation in the brain. DTI can thus provide information about

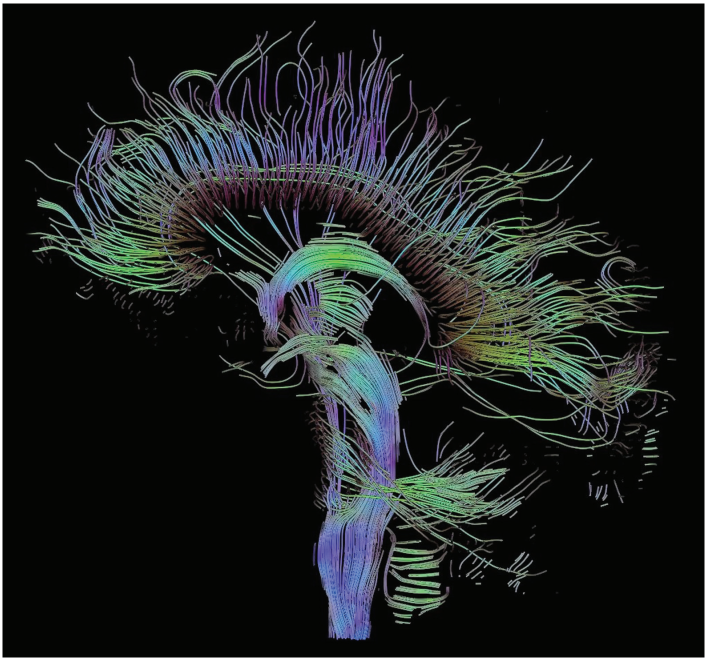

FIGURE 8 DTI measurement of the human brain. (Source: Thomas Schultz, https://commons.wikimedia.org/wiki/File:DTI-sagittal-fibers.jpg, CC BY-SA 3.0)

structural neural networks (that is, which areas are structurally connected with which other areas via complex linking networks, also called the *connectome*) in the human brain.

The structural organization of the human brain in terms of multiple, distributed, interconnected neural networks changes with development across childhood and adolescence in response to both genetics and environmental input (Tau and Peterson, 2010). For example, a recent DTI study investigated the relationship between childhood environment in terms of socioeconomic status (SES) and connectomics across the whole brain in children ages 6 to 12 in the United Kingdom (Johnson et al., 2021). The authors reported widespread, global effects of SES on the structural connectome, consistent with previous findings indicating that the environment influences brain structure (Johnson et al., 2021). The researchers also found that the structural connectome measures mediated the relationship between SES and cognitive ability as measured by standardized reasoning and vocabulary tests (Johnson et al., 2021); that is, these structural differences were related to functional differences in cognitive processing.

3.3 *Functional Magnetic Resonance Imaging* (*fMRI*)

fMRI data can also be recorded in an MRI machine (refer to Figure 6), with extra equipment that allows for the measurement of function in addition to structure. An MRI machine (also referred to as a magnet) with adequate power for structural and functional neural research costs multiple millions of US dollars.

Many neuroscience studies with children and adolescents use the fMRI method. In particular, they use a kind of fMRI called blood-oxygenation-level-dependent (BOLD) fMRI. Recall that neurons that are more active use more oxygen from the blood. BOLD fMRI tracks levels of oxygen in the blood. Brain areas that have a high ratio of blood-with-oxygen (oxygenated blood) and blood-without-oxygen (deoxygenated blood) are areas in which the neurons are most active. Blood flows into the areas with lots of oxygen, the neurons use it, then blood flows out of the areas with little oxygen. Thus, with the BOLD fMRI method, brain activity is not measured directly. Instead, neural activity is inferred by the degree of use of oxygen from blood flowing through different areas of the brain.

In studies that use neuroscience methods that depend on blood flow (like fMRI or *positron emission tomography*, *PET*), researchers must use both a *control condition* and an *experimental condition*. The experimental condition is what the researchers are most interested in. For instance, in a study of word reading, the experimental condition might involve having the participant read single words (e.g., RABBIT, HAND). It is important that a control condition be chosen to best isolate the factor of interest. If the control condition in our study was simply looking at a fixation point (+) on the screen, there would be many differences between the two conditions. For example, the fixation point involves much less visual input and does not involve any letters. Thus, any differences in processing between the two conditions could not confidently be attributed to word reading (differences could be due to visual or letter processing instead). A better control condition might be strings of the same letters as in the words but rearranged so as to not be readable (e.g., BIRBTA, NHDA). Now the basic visual and letter input are the same between the two conditions and the key difference is that only one (the experimental condition) involves reading meaningful words. Any differences between the two conditions in neural response can now more confidently be attributed to reading real words.

Most neuroscience studies based on blood flow measures do not publish the images recorded during the control condition and the images recorded during the experimental condition separately. If they did, what we would see—over and over again—is that the whole brain is active in both conditions (see Figure 9A, in which the experimental condition is labeled *task state* and the control condition is labeled *control state*) (Raichle, 1994). In these PET images,

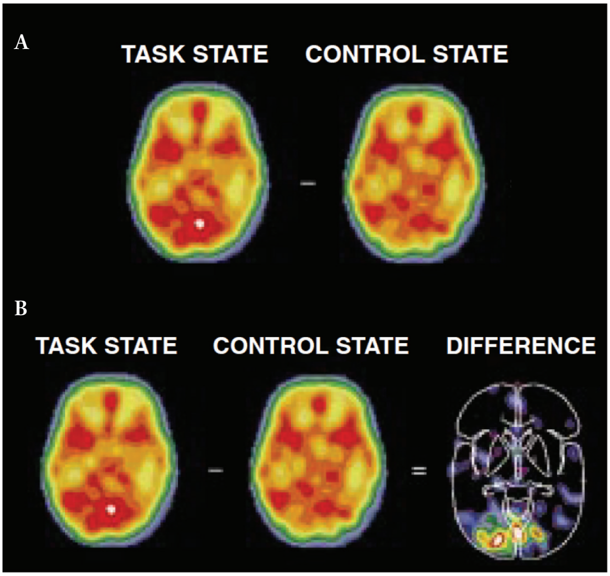

FIGURE 9 (A) Blood flow information showing that the whole brain is active in both the experimental (task state) and control conditions. (B) The subtraction image (far right) highlighting the differences in activation patterns between the two conditions. Used with the kind permission of the author (from Raichle, 1994, p. 62)

the white-red-yellow end of the color scale indicates greater blood flow, whereas the blue-purple end of the scale indicates less blood flow.

This overall widespread activity may be surprising to you because many people have the mistaken belief (or believe the *neuromyth*) that we use only some small percentage of our brains (e.g., 10%) (OECD, 2007). This is not the case. In part, this neuromyth might be based on the fact that we rarely get to see the actual data from the experimental condition and the control condition in studies that use blood flow measures like fMRI, PET (as in the images in Figure 9), or *functional near infrared spectroscopy* (*fNIRS*). Instead, we usually see images that are the *subtraction* (or difference) between the two conditions (see Figure 9B). The subtraction data analysis method, which is common, highlights the differences between the two conditions. It lets us know, for example, which areas of the brain are more involved in reading real words in comparison to looking at strings of the same letters (rearranged) that are not words. The areas we see colored are areas that were statistically significantly more active (e.g., had higher ratios of oxygenated to deoxygenated blood in BOLD fMRI studies) in one condition than in the other according to analyses using *p* values. But the images created in the subtraction also make it easy to forget that all of the other regions of the brain that are not colored showed a similar level of activity (statistically insignificant differences by *p* value) across both conditions.

Something else that we rarely get to see in published neuroimaging studies are the data from each of the individual participants in the study. In typical data analyses, the subtraction of the blood flow information in the control condition from the blood flow information in the experimental condition is done for each participant, and the resulting subtraction (difference) images are then averaged together across all of the participants (see Figure 10). The final picture that we typically see in published studies is the averaged (or *mean difference*) image. Thus, the individual differences that may be of most interest to educators can be lost in some of the analysis methods used in neuroscience, which often depend more on groups than individuals.

In addition, the mean difference image may not accurately represent any individual because it is an average across all participants in the study. For example, in Figure 10, the first participant on the top row shows greater activation in the experimental condition than the control condition (areas colored white and red) in a region on the left side of the brain, the second shows greater activation on the right, the third on the left, the fourth relatively balanced on the left and right, and the fifth greater activation on the right. The mean difference image on the bottom row—the result of mathematically averaging all of the images in the top row together—suggests bilateral (relatively equal on

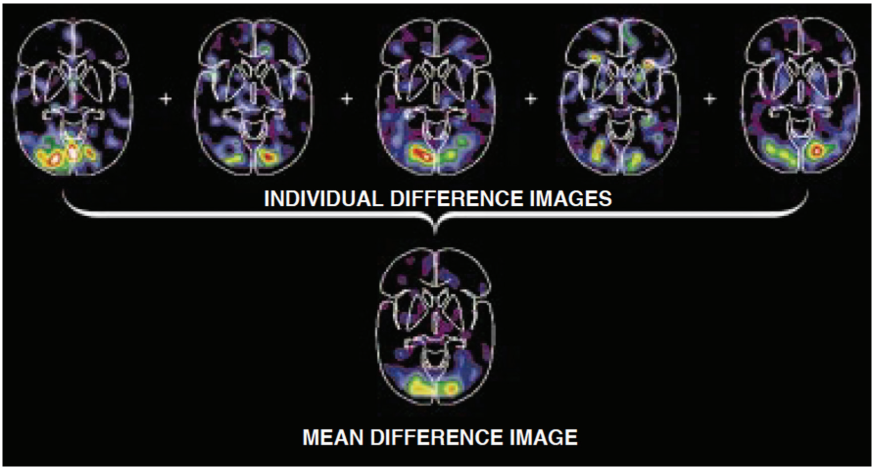

FIGURE 10 In data analyses, difference images for each individual (created by subtracting the control state from the task state activation pattern; top row) are averaged to create the mean difference image (bottom row) typically seen in a published article. Used with the kind permission of the author (Raichle, 1994, p. 62)

the right and left) activation. This description applies well to only one of the individuals in the top row (the fourth from the left). Whether in neuroscience research or with other kinds of data, mathematically, it is always possible that the average does not represent a single child in a group.

So, when you are looking at an image from an fMRI study, the colors superimposed on the structural MRI scan are an indication of which brain areas were statistically more active (as reflected by greater use of oxygen from the blood) in the experimental condition as compared to the control condition on average across all of the participants in the study. For example, Figure 11 illustrates which neural regions were statistically more active when participants were listening to normal speech as compared to listening to speech played backwards, on average, across 20 children ages 6 to 10 (Charbonnier et al., 2020).

It is important to understand what you are looking at and where an image came from in a neuroscience study if you want to incorporate neuroscience findings into your knowledge base on learning and development. Even then, how to use such neuroscience findings in education is not obvious. This has been called the *horizontal problem* in discussions about neuroscience and education (Willingham, 2009). Knowing that there is a specific neural region supporting a specific cognitive function does not tell us anything about how to design instruction for that function (Varma et al., 2008). In our example above, there is a region of the brain that is selectively more active when reading real words as compared to meaningless letter strings. So what? It is essential to recognize that this finding becomes useful to educators only in the context of

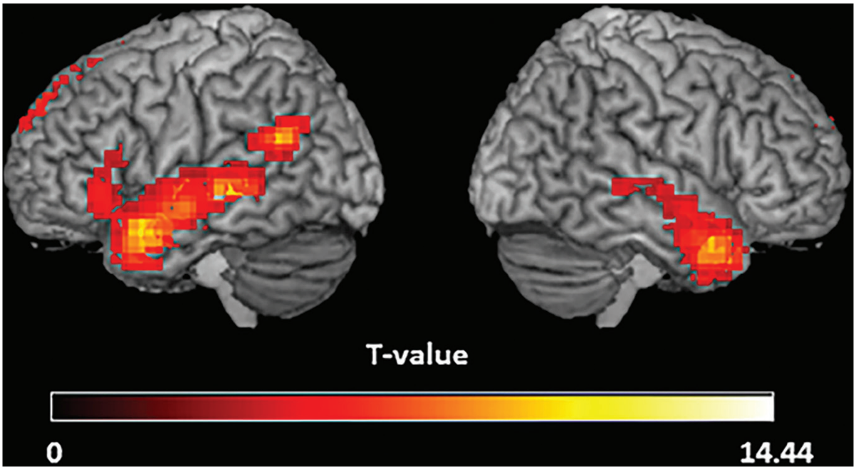

FIGURE 11 An image from an fMRI study showing which brain areas were statistically more active when children were listening to normal speech as compared to backward speech (Source: © Charbonnier et al., 2020. A functional magnetic resonance imaging approach for language laterality assessment in young children, Fig. 2 [modified to one condition], https://www.frontiersin.org/articles/10.3389/fped.2020.587593/full, CC BY 4.0)

other behavioral, cognitive, and educational theory and evidence at different levels of analysis.

For example, we know that learning to read in alphabetic languages involves mapping the sounds of spoken language (such as the sound that the letter *b* makes) to the letters on the page (to the printed letter *b*) (Adams, 1990). We also know that the phonics method of teaching reading, which emphasizes the mappings between letters and sounds, is part of evidence-based practice in teaching reading (National Institute of Child Health and Human Development, 2000). How does the neural word reading area finding fit into this established, research-based picture? It turns out that age 6, nonreading kindergarten children do not show activation in this region, but after being taught letter-sound correspondences for just a few hours do begin to show activation in this region when looking at words (as compared to strings of symbols)—even though they cannot yet read the words (Brem et al., 2010). In another fMRI study, as letter-sound correspondence knowledge and reading speed increased during the first months of reading acquisition (through classroom education), emerging specialized processing for words in this region also increased (Dehaene-Lambertz et al., 2018). This evidence indicates an association between educational practices (teaching and learning letter-sound correspondences in alphabetic languages during learning to read) and neural changes (developing specialization for word processing in this region). In the context of behavioral, cognitive, and educational evidence, this neural finding enriches our understanding of the process of learning to read.

3.4 *Resting-State Functional Connectivity MRI* (*rs-fcMRI*)

rs-fcMRI is based on the BOLD fMRI method, but without task and control conditions and with different data analysis approaches (Matthews and Fair, 2015; Vogel et al., 2010). As the name suggests, it is a measure of functional connectivity between brain areas when the participant is at rest (not being asked to perform a specific task). In other words, rs-fcMRI is a method that measures how activity in various regions of the brain is coordinated when a participant is not engaged in an explicit task. Thus, rs-fcMRI can provide a measure of the functional connectome (similar to DTI providing a measure of the structural connectome). This method has revealed that *intrinsic* (not related to a task) brain activity is functionally organized; that is, that regions of the brain are active in synchrony even when there is no specific task to perform. Whereas fMRI can be used to track development in task-related neural processing within specific brain regions, rs-fcMRI can be used to track development in non-task-related interactions between brain regions. Therefore, this method revealing co-activity among brain areas can provide insight into "the development of the brain's functional network architecture" (Vogel et al., 2010, p. 362). For example, interactions between neural regions tend to shift from being more local and short-range in children to becoming more distant and long-range in young adults (Vogel et al., 2010); different brain regions are constantly in communication, forming and re-forming networks, across development.

One of these networks that has captured the interest of educators is the default mode network (DMN) (Hodges and Wilkins, 2015), an organized network of brain regions that co-activate during non-goal-directed behaviors (Raichle, 2015; Raichle et al., 2001), such as when at rest in an MRI scanner. Based primarily on studies conducted with adults, the DMN is thought to "support cognition that is independent of immediate perceptual input", such as more introspective, self-referential, internal forms of cognition like imagining the future, recall of personal memories, or the perspective-taking required to understand another person's beliefs (Immordino-Yang, 2016; Konishi et al., 2015, p. 1). However, in a study with children ages 7 to 9 and adults using rs-fcMRI, the regions involved in the DMN were only sparsely connected in children in comparison to their more cohesive integration into a coherent network in adults, suggesting significant change in the construction of the DMN across developmental time (Fair et al., 2008). Given that, behaviorally, children ages 7 to 9 do have introspective abilities like recall of personal memories or perspective-taking related to theory of mind, this calls into question the developmental nature of the DMN (Fair et al., 2008), as well as the appropriateness of generalizing from studies with adults to children. Another rs-fcMRI study with children ages 6 to 12 also found that both overall connectivity among the brain regions involved in the DMN and network efficiency strengthened over developmental time, at different rates for different parts of the network (Fan et al., 2021). Although there have been claims that understanding the DMN is crucial for educators and policymakers and that neuroscientific knowledge about the DMN should guide practice, especially in light of the developmental evidence, "the direct relevance of DMN functioning to educational functioning is difficult to prove directly" (Immordino-Yang, 2016, p. 215; Immordino-Yang et al., 2012).

3.5 *Electroencephalography* (*EEG*) *and Event-Related Potentials* (*ERPs*)

EEG and ERPs, in contrast to fMRI, are methods that involve direct recordings of neural activity (Luck, 2005). When neurons are active, they create tiny electrical fields. When enough neurons are active at the same time and are oriented in the same way, the summary electrical signal can be strong enough to be recorded by electrodes placed on the scalp noninvasively (see Figure 12). Not all areas of the brain have neurons aligned in such a way that their activity can be recorded at the scalp, so EEG and ERP methods cannot be used to record from the entire brain. The equipment for recording and analyzing EEG and ERP data is appreciably less expensive (less than $US 100,000) than for fMRI research.

Whereas fMRI is good at revealing where information is being processed in the brain (has good *spatial resolution*), EEGs and ERPs are good at revealing the timing of information processing in the brain (have good *temporal resolution*). Because the brain is essentially a volume conductor, it can be difficult

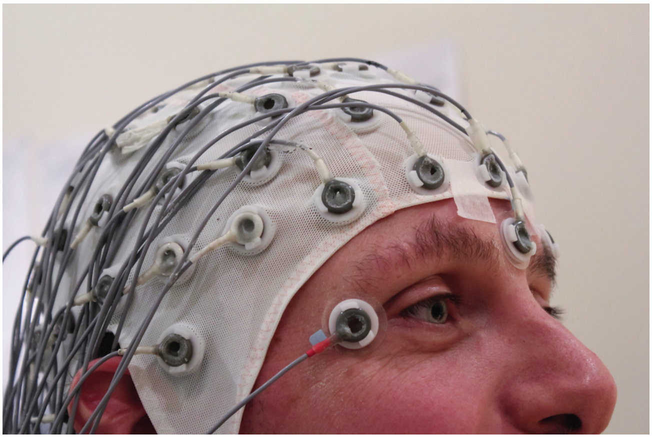

FIGURE 12 An adult research participant wearing an EEG recording cap with electrodes. (Source: Chris Hope, https://commons.wikimedia.org/wiki/File:EEG_Recording_Cap.jpg, CC BY 2.0)

to reliably localize the electrical signals to a specific source area (that is, we cannot tell exactly where the electrical signal is coming from in the brain); this creates poor spatial resolution for EEGs and ERPs. However, these methods track neural processing on the order of milliseconds (one millisecond is one one-thousandth of a second) and can show how information is processed in real time. In contrast, oxygenated blood cannot instantly appear where it needs to be, so fMRI has relatively poor temporal resolution. There is no single neuroscience method that can be used with children and adolescents that has both good spatial resolution and good temporal resolution (outside clinical contexts). It is important to recognize the limitations of neuroscience methods. It is also important for researchers to match the method they choose to their research question; sometimes they do not—another reason that readers need to be informed and critical consumers of neuroscience research.

The EEG is a continuous recording of all of the electrical activity that is recordable at the scalp. It is commonly analyzed in terms of frequency bands (see Figure 13). The frequency bands indicate the overall state of awareness and engagement of the participant. For example, prominent beta waves indicate awake and alert whereas prominent delta waves indicate deep sleep. EEG can also be analyzed in terms of *coherence*, a measure of the degree to which brain waves recorded at various electrodes placed across the scalp of an individual are in synchrony. Somewhat similarly to rs-fcMRI, this reveals information about functional connectivity in networks of neurons. Recently, researchers have considered a new way to use EEG coherence: investigating how much EEG recorded from different students in the same classroom and EEG recorded from the teacher in that classroom are in synchrony (Bevilacqua et al., 2019; Dikker et al., 2017).

The ERP, which is a derivative of the EEG, is more commonly used in cognitive and affective studies. ERPs reflect how a participant's brain processes specific types of information (not just overall state of arousal). An ERP is created by recording EEG from electrodes placed on the scalp and presenting numerous instances (often from 50 to hundreds) of a stimulus type or types. As illustrated in simplified form in Figure 14, the portions of EEG that occurred just as each stimulus type was being presented are then averaged together (Hillyard and Kutas, 1983). In that mathematical averaging process, the relatively consistent electrical activity in response to a stimulus type is strengthened. In contrast, the other electrical activity unrelated to processing the stimulus type is weakened, and eventually averages to zero because it is random with respect to stimulus presentation. So, what emerges from the averaging process is the brain's response to a given stimulus type, or, put another way, the electrical potential related to a specific kind of event: the ERP waveform.

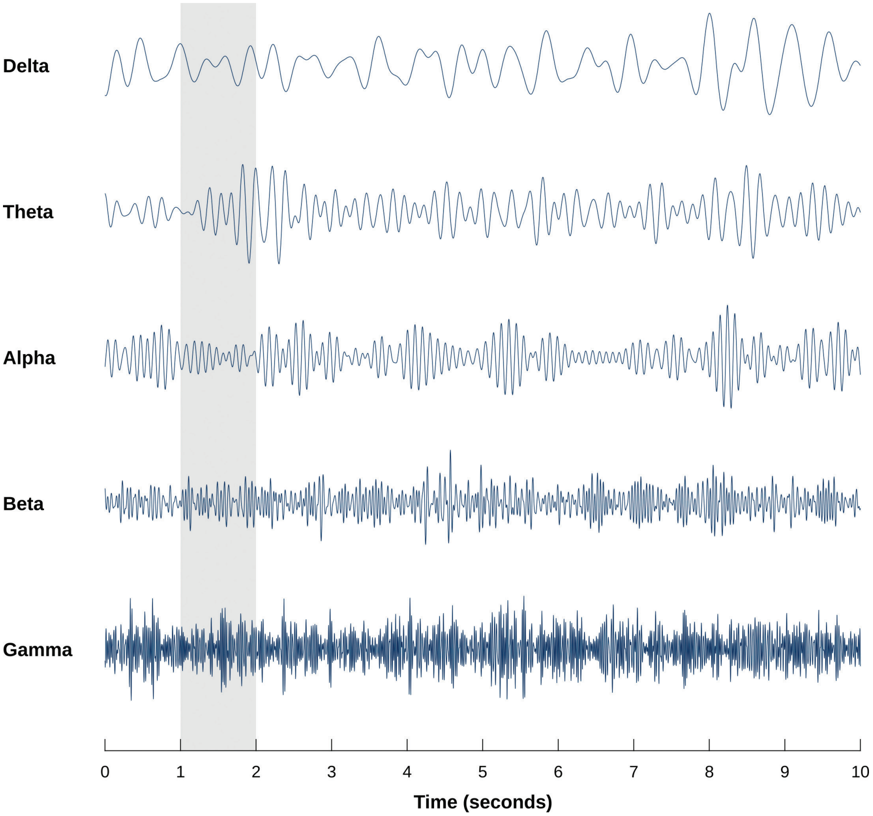

FIGURE 13 An illustration of the frequency bands of the EEG (Source: Laurens R. Krol, https://commons.wikimedia.org/wiki/File:EEG_Brainwaves.svg, public domain)

Each of the peaks and valleys of the ERP waveform has been related to a specific kind of processing. For example, the "N1" (a negative-going peak early in the waveform; refer to the bottom panel in Figure 14) is related to selective attention (Luck, 2005). The size (*amplitude*) and timing (*latency*) of a peak or valley can be compared across conditions or groups in an ERP experiment to reveal processing differences. For instance, in an experiment investigating the effects of a computerized intervention targeting language skills development in children ages 6 to 8, the experimental group of children receiving the intervention showed an enhanced auditory selective attention effect (greater N1 amplitude) after training, in comparison to a no-treatment control group (Stevens et al., 2008). Thus, ERPs can show how information is processed in real time in the brain in terms of relative neural resources used and how that changes over time with an educational intervention.

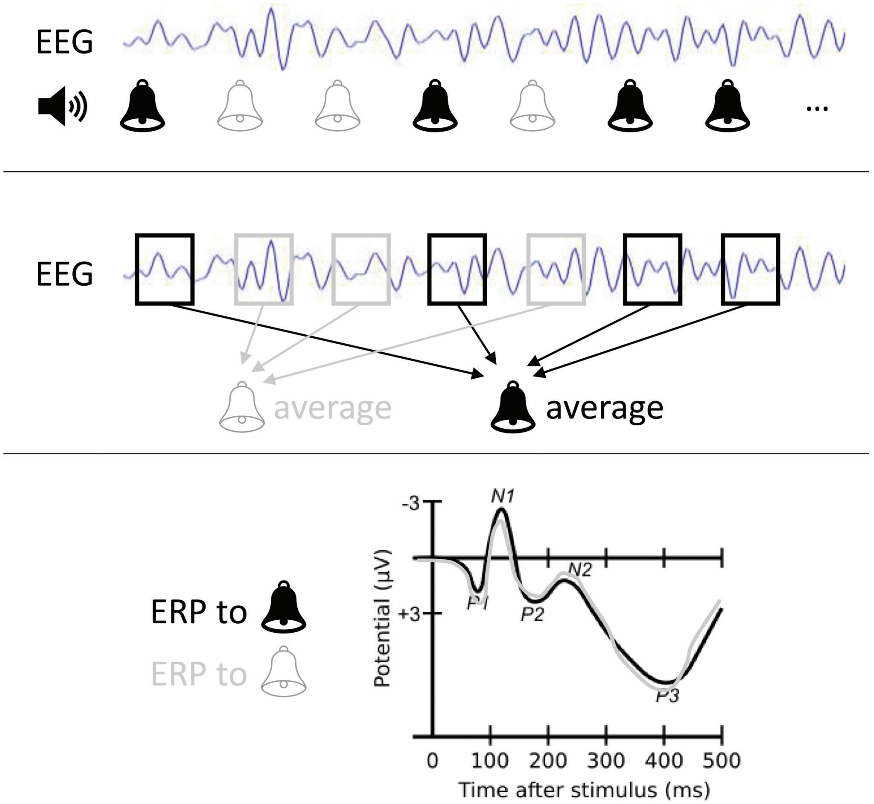

FIGURE 14 Deriving the event-related potential (ERP) from the electroencephalogram (EEG). In this example, two auditory stimuli (indicated by the black bell and the gray bell) are presented multiple times as the EEG is recorded (top panel). After the participant leaves the lab, the portions of EEG that occurred just as each black bell sound was presented are averaged together and the portions of EEG that occurred just as each gray bell sound was presented are averaged together (middle panel). What emerges are the auditory ERPs to the black bell and gray bell sounds (the neural electrical potentials specifically related to each type of sound event; bottom panel). Each of the peaks and valleys in the ERP waveform is related to a specific type of processing. Beta EEG (in blue, top and middle panels) (Source: Hugo Gamboa, https://commons.wikimedia.org/wiki/File:Eeg_beta.svg, CC BY-SA 3.0; ERP waveform [bottom panel]; Mononomic, https://commons.wikimedia.org/wiki/File:ComponentsofERP.svg, CC BY-SA 3.0 [gray trace added])

4 Proof or Persuasion? The Power of Brain Images

Brain images, particularly those based on blood flow measures such as fMRI (see Figure 15), can be fascinating and persuasive. Some studies have shown that people find results that include brain images (as compared to those

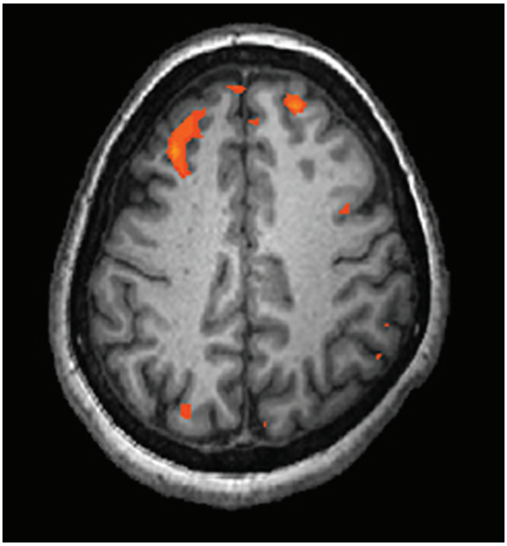

FIGURE 15
Another example of an image from an fMRI study. Recall that the color indicates areas with statistically significant differences in activation between conditions, plotted on top of the structural MRI image (Source: https://wikieducator.org/images/8/84/CNX_Psych_03_04_fMRI.jpg)

without them) more believable (McCabe and Castel, 2008)—as if the picture itself is somehow proof of something—whereas others have found no such effect (Michael et al., 2013). Even without images, although also not always the case (Hook and Farah, 2013), some people may find explanations including neuroscience terms more convincing (as compared to those without such terminology) (Weisberg et al., 2008). So-called "brain-based" educational products regularly capitalize on these persuasive tendencies (Sylvan and Christodoulou, 2010) despite the fact that the actual evidence base for such products is often highly questionable (Alferink and Farmer-Dougan, 2010; Bruer, 1999; Jorgenson, 2003). Interpretations of brain images and their potential implications can be provocative—and misleading. As we have emphasized throughout, the leap from a brain scan image to a classroom practice or educational policy is a leap across several levels of analysis (refer to Figure 5) and does not typically take into account the complexity of either the authentic educational context or the brain itself. Scientific literacy—including an understanding of research generally and neuroscience research specifically (e.g., what exactly an fMRI picture depicts)—may help educators to be more critical consumers of both educational products of this type and the actual research.

5 Ecological Validity

Early attempts to connect neuroscience and education often depended on the findings of cellular neuroscience studies with nonhuman animals (Bruer, 1997). For example, a series of studies with rats showed that young rats raised in complex environments with other rats and varied objects learned (ran mazes) more quickly and had thicker brains with more neural connections than rats raised in isolation (Black, 1998; Greenough et al., 1987). In the education world, these findings were "translated" into passionate calls for early enrichment for infants and young children. However, several important aspects of these studies and their findings were ignored in the effort to interpret the findings for a broader audience. For example, the cages with the complex environment (which became the "enriched" environment in educational translation) were just simplistic attempts to mimic in the lab the typical environment of a rat in the wild and were in no way "enriched" in comparison to the natural environment of a rat. Further, the effects were reversible: The behavioral performance gains and neural changes observed in rats placed in cages with the complex environment disappeared if those rats were then placed in cages with a less complex environment. Finally, similar behavioral and neural effects could be achieved in older rats put into the same complex environment later in life (Greenough et al., 1987; Juraska et al., 1980). Thus, one more accurate conclusion from these studies might be that an impoverished environment relative to a more typical developmental context may have comparatively negative impacts on rat brain development and ability to run mazes. Another more accurate conclusion might be that the brain adapts to the more complex or stimulating, or the simpler or impoverished, demands of the environmental context no matter the age of the rat. These studies provide a wonderful example of lifelong *neuroplasticity*, a factor important throughout development, rather than a rationale for marketing programs and products for infants and children between zero and three years of age.

Overall, extrapolating from neuroscience studies with rats to child development and learning in classrooms sorely lacks *ecological validity*. Ecological validity means that the research was conducted in a way such that it is more likely to generalize to real-life settings. Indeed, this kind of neuroscience research seems unlikely to directly contribute anything specifically useful to real-life educational practice. Although we may not agree on the goals of education, we can probably agree that having children run mazes faster is not one of them. Often ostensibly based on such neuroscience research, there is a great temptation to declare that "the brain learns" in certain ways and to enumerate three or eight or ten grand principles about "how the brain learns" that every teacher must know—even though the referenced research does not involve instructional strategies or curricula (never mind children) in any way (if any neuroscience literature is even referenced at all to support the claims). There is not one best way to teach, nor one best way to learn (Daniel and Poole, 2009). Learning is contextualized and dynamic and involves multiple processes and neural networks. The brain both constrains learning and development and is shaped by learning and development. A child learns in interaction with the environment, often in interaction with other people, and builds on what she already knows. This sort of basic neuroscience research cannot capture this complexity at human scale (e.g., refer to Figure 5) and so is ill-fit to inform education, by itself, particularly in terms of "best practices".

Although perhaps not as acute, but along the same lines, caution should be taken in extrapolating from findings from neuroscience studies with young adult participants to applications with young children (e.g., as discussed regarding rs-fcMRI studies of the DMN). Moreover, most studies with young adults are conducted with university students. This is a select group of the population, and a group that has had extensive experiences with classroom learning. Practice with learning over more than a dozen years likely has some effects. It may not be legitimate to assume that learning in a 19-year-old university student is the same as learning in a 9-year-old or fourth-grade student. Indeed, from a developmental perspective, it is not that sensible to assume that very much processing is identical in a 9-year-old and a 19-year-old except at the broadest levels of analysis: Development is, by definition, a process of change over time. Furthermore, most research studies (an estimated 80%) are conducted in Western, educated, industrialized, rich, and democratic societies (who represent only an estimated 12% of the world's population); findings from such studies may not be representative of other human populations and contexts (American Psychological Association, 2010; Henrich et al., 2010).

Related to these issues of ecological validity, most neuroscience studies involve a very small number of participants (around 20 is not unusual, and studies with fewer participants have been published in peer-reviewed journals), so basic generalizability of the findings is limited. However, some databases include developmental neuroimaging data as well as data from other levels of analysis (e.g., genetic, neuropsychiatric testing, and standardized test data) from the same participants, numbering in the hundreds or even thousands. For example, the Generation R Study in the Netherlands (White et al., 2013); the developmental segment of the Chinese Color Nest Project: Growing Up in China (Dong et al., 2020; Yang et al., 2017); and the Child Psychiatry Branch of the National Institute of Mental Health study (Giedd et al., 2015), Philadelphia Neurodevelopmental Cohort study (Satterthwaite et al., 2016), Pediatric Imaging, Neurocognition, and Genetics (PING) study (Jernigan et al., 2016), Lifespan Human Connectome Project in Development (HCP-D) study (Somerville et al., 2018), and the Adolescent Brain Cognitive Development (ABCD) study (Casey et al., 2018) in the United States. For instance, ABCD is a multi-site study involving about 12,000 children ages 9 to 10 whose biological and behavioral development will be tracked over 10 years, throughout their adolescence into young adulthood. Structural (MRI) and functional (fMRI) brain measures are being taken every two years as part of the study protocol. In an early analysis of data from over 11,000 (!) children, activity in a frontoparietal network during a working memory task in the magnet (but not during other tasks) was related to individual differences in working memory performance on a standard behavioral task (Rosenberg et al., 2020). Unfortunately, none of these large-scale studies was designed with utility for educational practice as a priority. Beyond increasing the number of participants and taking multiple measures at different levels of analysis so as to constrain interpretation of neuroscience findings (any interpretation of a given finding must be consistent with interpretations of all other kinds of data collected), there are other discussions in the literature about how fMRI studies could change to be more usable in education (Seghier et al., 2019).

When considering the ecological validity of neuroscience research in relation to education, as with any other research, it is also important to take into account the culture and values of education. Even if we had a neuroscience method that was completely accurate in showing us when some kind of information had been learned—for example, if we had a "neural signature" of learning for a mathematical concept—it seems unlikely that it would be of value on its own. First, if we did find this neural signature in a child but the child could not explain the mathematical concept to us in a way that revealed understanding, we would likely discount the neural evidence as an invalid indicator of learning and depend on the behavioral evidence. Second, even if it were valid, it is both unlikely and impractical that we would put every child in a magnet in order to see if we could find this neural signature as a form of assessment. This is because, currently, we value the behavioral level of analysis for learning in education (Bowers, 2016) (refer to Figure 5). If there is a conflict between evidence sources, educators will most likely believe and act on what the child in front of them is saying and doing rather than the results of a brain scan.

Finally, because of the nature of neuroscience methods, most neuroscience studies are conducted in the controlled environment of a research laboratory. It is currently impossible to bring a magnet to a primary school, and even though EEG studies can be conducted in a classroom (Bevilacqua et al., 2019; Davidesco et al., 2021; Dikker et al., 2017), interactions while wearing caps with electrodes and wires on your head are not necessarily normal. Although we are vitally interested in the complexity of classroom learning as educators, neuroscience research (like most empirical research) requires control of variables—isolating and manipulating one variable of interest to discover its effects while holding all other variables constant. This thin sliver of real-life complexity may be able to inform education in some way, but it necessarily lacks the ecological validity of an in-classroom study without such constraints. In brief, the methods used in neuroscience (taken alone) are a poor fit for "handling the complexities of learning environments" (Turner, 2011, p. 223).

CHAPTER 3

Using Neuroscience Research in Education

The Fundamental Issue of "Translation"

Nonetheless, educators are often enthusiastic about using findings from neuroscience research in their practice (Pickering and Howard-Jones, 2007). Empirical research findings *can* support classroom application in teacher training (Willingham, 2017) but "the evidence on how best to deploy these findings is still very weak" (Gorard et al., 2020, p. 570). Moreover, as emphasized above, a prerequisite to using neuroscience evidence in education is that educators understand that evidence, where it comes from, and what it means (and does not mean). Vague claims about "neuroscience research shows …" are not sufficient: Educators need to be critical consumers, asking: What kind of research, with which participants, including what conditions, using what outcome measures, resulting in what effects, with what interpretations, with what relevance? With training, teachers can "become effective readers and critical evaluators of research findings … ask crucial questions, know how to find answers, [and] make connections across different sources of evidence" (Ansari and Coch, 2006, p. 148) to create usable knowledge.

In an evidence-based model of education, educators have a dual role as both critical consumers and producers of evidence (Davies, 1999). It is not a new call for teacher training and professional development that educators need to be able to both engage with research and engage in research in principled ways. For example, from the 1970s:

> There are strong arguments for developing a cadre of teacher-researchers committed to working on classroom problems … to expect teachers to contribute to the development of their occupational knowledge seems reasonable; to the extent that they do, their future standing and work circumstances will benefit. (Lortie, 1975, pp. 242, 244)

From the 1990s: Educators

> need to critically read and analyze the research in order to separate the wheat from the chaff. If educators do not develop a functional understanding of the brain and its processes, we will be vulnerable to

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> pseudoscientific fads, inappropriate generalizations, and dubious programs. (Wolfe and Brandt, 1998, p. 10)

And from this century: This

> raise[s] the issue of the scientific illiteracy of the teacher population … The growing interest of teachers in informing their pedagogical practice with scientific evidence from brain research highlights the need to redesign teacher training programs … to include basic science literacy and a basic understanding on how to read science literature. (Gleichgerrcht et al., 2015, p. 176)

But what might engaging *in* research (knowledge production) and engaging *with* research (knowledge consumption) look like in translation?

1 Engaging in Research: From Neuroscience Research to Teaching Practice

To be clear, findings from neuroscience research "cannot simply be translated into pedagogical knowledge" or practice (McIntyre, 2005, p. 359). One reason is that primary source neuroscience research is conducted and organized from a scientist's perspective, to be used for developing new knowledge, not from a teacher's perspective, to be used to help students learn (Cochran, 1997, para. 5); some translation or adaptation is therefore necessary before the research can inform practice. Another reason, as noted, is that the vast majority of neuroscience studies are not conducted in classroom contexts; therefore, the findings from these studies are not directly applicable to pedagogical practices and "need to be tested—rigorously and scientifically—in the classroom before any 'educational application' or 'translation' can become clear" (Coch and Ansari, 2009, p. 546). In short, lab-based neuroscience findings must undergo "contextual vetting" before use as a pedagogical tool in a classroom context (Daniel, 2012, p. 251).

Unfortunately, there are currently no established guidelines for this translational process in education (de Bruin, 2016), so developing applications and evidence of their utility most often becomes the professional responsibility of teachers. For teachers to be effective in this role, such translation of brain research into teaching practice needs to be accurate and principled (Ansari and Coch, 2006; Donoghue and Horvath, 2016). Some have suggested that, parallel to evidence-based practice in medicine, researchers and educators should test lab findings in small classroom studies and then larger RCTs (Kane, 2017). In moving toward more "inclusive education to extend to the involvement and engagement of teachers in the research enterprise", there are models in which teachers, sometimes along with researchers, generate and conduct research-literature-inspired new studies or conceptual replications of laboratory research in their classrooms (Brown, 2022, p. 189; MacMahon et al., 2022). In a review of ways to get evidence into use in education, "having the users actually do the research" was found to be a "promising approach" (Gorard et al., 2020, p. 570). If the teacher-tested practices have significant (both statistical and practical) and valued impact, they could then be introduced into wider pedagogical practice through teacher training, with continuous monitoring thereafter (Roediger III, 2013, p. 2).

However, most teachers have little experience conducting their own research to produce usable evidence, as Garrison (1988, p. 488) noted decades ago:

> Very few classroom teachers conduct, much less publish, research on teaching. The truth of this statement is so widely known that the reader might well wonder why it even needs mentioning. Yet when considered correctly this is a genuinely strange if not remarkable statement, Is it not odd that teachers have no part in the production of the scientific knowledge that is to empower them as professionals? Unbelievable!

More recently, in a survey and interview study in Australia, pre-service teachers who had engaged in research had more positive attitudes towards research, but only one-third of participants reported research experience (Guilbert et al., 2016). In a survey as part of an evidence-based teaching project in the United Kingdom, 45% of classroom teachers reported no experience of engaging in research (Hammersley-Fletcher et al., 2015, p. 29). Of all school staff surveyed, 54% of respondents reported having done some research-oriented professional development in school, 37% said they had no experience of doing research, and only 9% felt they were experienced teacher-researchers (Hammersley-Fletcher et al., 2015, p. 29). In reality,

> teachers are researchers. They collect enormous amounts of data each day, and they rapidly evaluate and make decisions based on this data … What teachers are not good at is doing anything formal with this data, [although] … all this data could … be used as evidence to inform practice. (Kelleher and Whitman, 2017, para. 1)

Thus, this approach to translation would require substantial change in teacher education and professional development programs to include evidence-based, research-specific training and experiences as well as a formative method for developing a contextually-relevant knowledge base for educators.

In the context of neuroscience research, this approach to translation might involve teachers working with findings from neuroscience studies on learning and development to spark new ideas and yield hypotheses for practice that require additional research design and classroom-based assessment before becoming useful to educators. For instance, in a study of 80 K–12 classroom teachers in Israel who worked to develop relevant skills during a three-year project, the authors reported that "neuroscience knowhow can initiate directions for devising new learning practices … participants indicated that they were able to conceive of new ways of thinking and acting as teachers" (Friedman et al., 2019, p. 127). Similarly, 14 practicing teachers in another case study were documented using educational neuroscience concepts learned in a short graduate course to "reconsider, re-envision, and re-design their lessons" as well as affirm the continued use of some current practices and justify exploring new techniques (Chang et al., 2021, p. 1). Thus, there is some evidence that teachers themselves can evaluate relevant neuroscience findings and work to translate them into classroom practice (Hardiman et al., 2012, p. 137)—although not necessarily in principled ways. That is, this is not the research component of evidence-based practice without some sort of formal evaluation of the implementation and efficacy of these new, neuroscience-inspired ideas and practices to determine the legitimacy, impact, and unintended consequences of these "translations".

These are crucial issues that can undermine attempts to connect neuroscience research and educational practice. For example, a handful of studies claim to show that teachers exposed to key concepts in neuroscience realign their pedagogical practices (Dubinsky et al., 2013; Dubinsky et al., 2019; Schwartz et al., 2019). Educators in these studies learned that, for instance, "learning strengthens a set of electrical and chemical events at the level of individual neurons that, over time, result in functional associations distributed throughout the brain, and the act of remembering opens up this synaptic set for further plasticity" (Dubinsky et al., 2013, p. 319). However, close examination of a recent report of non-science K–12 teachers in the United States successfully learning such "basic cellular processes studied in neuroscience" and using that knowledge to "transition to using student-centered pedagogies" (Schwartz et al., 2019, p. 89) suggests that limitations of the study (many noted by the authors themselves) bring interpretation of the pedagogical findings into question. First, the study involved only 14 teachers, 13 of whom had self-selected to enroll in both a Mind, Brain, and Education graduate program and the research study; the findings may not generalize beyond this very small, select, and motivated group. Second, this was a quasi-experimental study with no control group for comparison. Third, successful learning was determined by improvement on eight multiple choice questions and a task involving drawing and labeling a neuron, rather than any sort of deep probe of understanding or shift in mental model of learning (conceptual change). Fourth, fewer than half of the annotated lesson plan changes (the only measure of transition to student-centered pedagogical practice) were judged to involve neuroscience in any way. Fifth, there was no measure of student impact or improvement. Lastly, the experimental teaching modeled student-centered pedagogy, thus confounding any effects of the teaching method and the neuroscience content (that is, two key variables were manipulated at the same time, disallowing determination of their separate effects). Therefore, this is not incontrovertible evidence for any direct impact of neuroscience knowledge on teaching practice. As noted by Perry and colleagues (2021, p. 8),

> applying the principles … is harder than knowing the principles and one does not necessarily follow from the other. Principles do not determine specific teaching and learning strategies or approaches to implementation … [They] interact and should not be considered in isolation from each other, or without taking into account wider practical and pedagogical considerations.

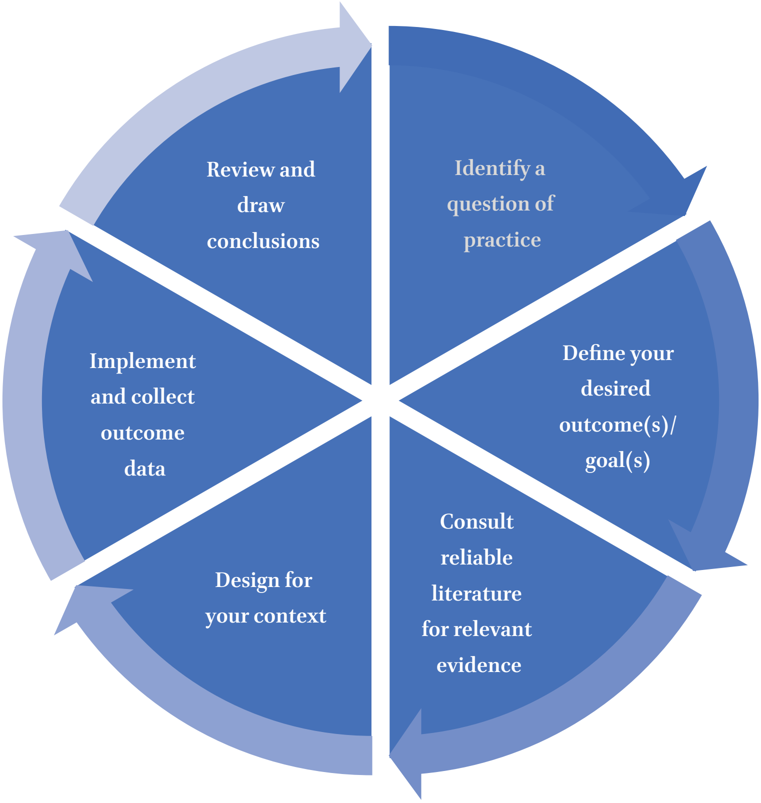

FIGURE 16 A cycle for conducting research in the classroom, beginning with identifying a question or problem of practice

Thus, we maintain that most findings from neuroscience studies need to be reimagined in a proper, research-based way (that is, through further carefully designed, classroom-based study) for application to teaching practices.

Theoretically, integrating a research perspective into teacher training—including instilling an interdisciplinary habit of mind and a culture that can inform an underlying model of evidence-based education from the beginning—is likely to decrease illegitimate mistranslation and misuse of neuroscience findings in education. (It is important to note that this works both ways: education is misrepresented and misused in the neuroscience literature, as well.) Practically, at a basic level (see Figure 16), if educators can use neuroscience evidence to spark a well-formulated question related to their practice, specifically define their desired outcomes or goals, consult relevant literatures and critically consider the extant research evidence related to that problem of practice, use their professional judgment to apply that evidence in some way that fits with other practices in their classrooms (that is, develop and design a new practice or method with fidelity to the literature and that is consistent with their other classroom practices and methods), implement and collect outcome data (including data associated with potential unintended consequences), and then review and conclude by carefully assessing and evaluating the outcomes of that application in terms of whether and how their question has been answered, whether they need to iterate or modify and try again, whether they need to try something else entirely, and what new questions have arisen (Rose and Eriksson-Lee, 2017), this is the backbone of a principled translational process. From the perspective of an action research model, a teacher-scholar model, or a critical inquirer model, research "empower[s] teachers to engage in the process of knowledge production" (Garrison, 1988, p. 500). Importantly, research knowledge and practical knowledge must commingle in this translational approach: "Good teachers need to engage actively with educational research; rather than replacing the irreducibly craft-based elements of their work, an iterative research-teaching relationship can support and expand them" (Winch et al., 2015, p. 211).

2 Engaging with Research: From Neuroscience Research to Knowledge Base on Learning and Development

Although there are few, if any, specific connections between neuroscience research and teaching practice without proper translation, findings from neuroscientific studies of learning, cognition, and social and affective development (for example) might more directly inform teachers' knowledge bases—in particular, content knowledge about learning, learners, and their development (Cochran et al., 1993). It is “reasonable to expect that there’s some threshold of knowledge that teachers need to reach in order to apply evidence-based practices in their classroom” (Schwartz, 2022). Neuroscience research may not be able to tell educators what to do in terms of specific pedagogical practices but may be able to help educators better understand what their students are doing. That is, neuroscience evidence may augment educators’ knowledge bases on learning and development and thereby inform their mental models. However, as has been stressed, a prerequisite to incorporating neuroscience evidence into their knowledge bases is that educators understand the evidence, where it comes from, what it means (and does not mean), and how it can be integrated (or not) with knowledge based on their own classroom experiences and their knowledge of their students from other sources.

Critically examined by educators as consumers of evidence, neuroscience research can provide important insights that are not obvious from behavior alone. Consider the following examples. First, neuroscience research can provide more nuanced views of key skills. For example, although educators might think about a concept like attention (as in *Pay attention, children!*) in general terms, neuroscience studies have documented, for instance, that selective attention and sustained attention involve different neural networks (Petersen and Posner, 2012; Sarter et al., 2001; Yantis, 2008). Breaking down complex skills, like attention, into component parts may help educators better understand students who are struggling. For example, is a child having difficultly focusing on what needs to be focused on (selective attention) or keeping focus over time (sustained attention)? Each requires a different approach to develop different skills and neural networks—beyond just *Pay attention!*

Second, neuroscience measures can be combined with behavioral measures to explore convergence and divergence. If two groups of children exhibit the same behavior, such as being able to solve two-digit multiplication problems correctly, one possibility is that they are using the same neural system to do so; another is that they are using different neural systems. If the children are using different neural systems, this pattern could inform a model of the learner based solely on behavioral evidence by acknowledging that the same behavioral outcome can involve different underlying neural processes. Further, it may be important to be aware of the idea of these different neural foundations when, for example, building the next mathematical skill in the curriculum that depends on the previous skill.

In a similar example from a research study, children and adults performed the same mental arithmetic tasks with the same level of correct responses behaviorally, but younger children used more prefrontal cortical networks in comparison to adults, who used more parietal networks while performing the tasks (Rivera et al., 2005). Once again, the observable behavioral outcome is the same, but the contributing underlying processes are different. In this case, the finding reinforces that development itself involves both quantitative and qualitative changes over time: The brains of children are not just little versions of the brains of adults, and we cannot assume that findings from adults can be applied to children.

Along the same lines, if two groups of children exhibit different behaviors, for example, students who are at grade level and below grade level for reading, they may be using the same neural networks to a lesser or greater extent or different neural systems altogether. For instance, in one fMRI study with children, activation levels in an area not typically used for reading predicted which struggling readers would show gains in reading a few years later, suggesting recruitment of additional neural resources to learn to read rather than strengthening of the typical reading system (Hoeft et al., 2011). *Equifinality* is the concept that there can be different pathways to a similar outcome.

Finally, neuroscience research can be used to corroborate educational theory and practice. In particular, neuroscience research can provide potential explanations for why or how specific approaches do or do not work in terms of underlying neural processes (Howard-Jones et al., 2020; Howard-Jones et al., 2016; Thomas, 2013). For example, studies revealing that brain networks involved in sound (phonological) processing are not as active in children with dyslexia during word reading in comparison to typical readers of the same age (Simos et al., 2000) provided support for the theory that dyslexia involves a difference in phonological processing (Shaywitz, 1996). As further evidence in support of both this theory and practice, children with dyslexia who received educational intervention involving phonological training showed not only normalized activation levels in neural phonological processing networks during reading but also gains on standardized tests of reading (Simos et al., 2002). Teachers should not be providing instruction in phonological awareness *because* of the neuroscience evidence—they should be providing instruction in phonological awareness because that method of instruction is effective (National Institute of Child Health and Human Development, 2000). Fortunately, the proper provision of such instruction is consistent with what is currently known about the development of reading in alphabetic languages from neuroscience, behavioral, *and* pedagogical research. In this way, theory, practice, and research findings can mutually constrain and support each other and provide consistent evidence to build an integrated knowledge base and inform models of learning and development.

CHAPTER 4

Conclusion

As a field, education is replete with ideas and practices that are not based in research; moreover, clear empirical evidence shows that many of them do not work (Goodwin, 2021). One reason that these ideas and practices will not go away is that they are already integrated into educators' mental models, and it takes deliberate, effortful work to extract and counteract them. Replacing these ideas and integrating more accurate behavioral and neuroscience research evidence on learning, development, and teaching into educators' knowledge bases and, ultimately, mental models, would involve significant changes in most teacher education programs. Indeed, it would involve a *multilevel boundary crossing approach* among teacher education programs (both pre-service and in-service), schools, and the scientific research community (Akkerman and Bruining, 2016, p. 240).

This is unlikely to happen without support at the policy level. Education systems are embedded in cultures and communities (refer to Figure 5), and they are guided by the value systems in those contexts. Policy—and the related allocation of limited resources—represents the values of those who implement it. In many countries, policy serves to guide, provide resources for, limit, or even dictate specific pedagogical practices, orientations, models, and tools. Without the support and impetus provided by sound policy, evidence-based changes in education are unlikely to occur. Given their role in charting a course and assigning resources, policymakers are integral to the development of high-quality teacher training and educational systems and provide crucial leadership in encouraging the use of science to support those systems. Rather than seeking and endorsing a finite set of so-called best practices or initiatives, policymakers should consider developing the policies and processes to train educators in scientific literacy, encourage the development of a common language of practice, and resource the translational infrastructure necessary to move promising findings from the lab into practice (and vice versa). Further, policymakers can use evidence not only to evaluate and decide which policies to adopt, but also to guide, refine, and evaluate the impact of those policies over time.

In summary, using neuroscience findings to improve teaching and learning would involve:

– Adopting an empirical perspective in education. A deliberate decision to endorse the scientific method as a standard of proof in education and a

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commitment to promoting the use of empirical evidence, at the levels of national policy, school districts, schools, and administrators and teachers.

- Working towards evidence-based practice in education. Integrating research evidence, classroom experiences, and student characteristics into teachers' knowledge bases—and, eventually, mental models—about learning, development, and teaching.
- Strengthening scientific literacy in educators. Enhancing teacher training to include the skills and concepts fundamental to gathering evidence and using research and data in the context of the classroom in critical, principled ways as both consumers and producers.
- Developing neuroscientific literacy in educators. Enhancing teacher training to include the skills and concepts fundamental to understanding neuroscience research findings, where they come from, what they do and do not mean, and whether and how they can be integrated with other knowledge sources and classroom practice.
- Critically thinking about translation of research findings for use in the classroom. Developing a suitable translational process and encouraging and supporting the professional role of the teacher as a generator of evidence that can more directly guide teaching.

In closing, the conceptual change that we are advocating here is a shift to models of learning, development, and teaching informed by a deeper understanding of using research evidence in critical, principled ways, supported through teacher training programs and educational systems and policies that value the use of scientific evidence. Building a culture of evidence "has the potential to be transformative in teacher education" (Cochran-Smith and The Boston College Evidence Team, 2009, p. 458). In part, this is because evidence-based practice "promotes lifelong learning" (Spring, 2007, p. 611)—something to both support and encourage not only in our students but also in our educators.

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Figures

About the Authors

Donna Coch is Professor in the Department of Education at Dartmouth College. She majored in Cognitive Science as an undergraduate at Vassar College, earned an MEd and EdD in Human Development and Psychology from Harvard University Graduate School of Education, and held an NIH-funded postdoctoral position at the University of Oregon Brain Development Lab. At Dartmouth, she supervises the undergraduate Reading Brains Lab. Using both event-related potential and behavioral measures, her research explores neural correlates of different aspects of reading and reading development. Professor Coch teaches courses on education, learning, and development; the development of reading; atypical developmental pathways; disability in children's literature; and what works in education. Goals of both her research and her teaching are to support students in developing interdisciplinary knowledge bases and to make meaningful, useful connections across the fields of psychology, neuroscience, and education.

David B. Daniel is Professor of Psychology in the Department of Psychology at James Madison University, where he founded the Teaching and Learning Lab. He earned an MA and PhD in Life-Span Human Development at West Virginia University. His scholarship is focused on developing usable knowledge for teaching and learning, including the synthesis and translation of scientific findings to authentic teaching and learning contexts, policy, and curricula development, as well as the communication of effective practice to those involved in research and development.

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Connecting Neuroscience with Education... makes a strong case for shifting toward models of learning, development, and teaching that are informed by a deeper, more critical understanding of research evidence. It advocates for using evidence in principled ways, supported by teacher education programs and education systems that value scientific inquiry. Building a culture of evidence has the potential to be transformative for teacher education and by extension, for broader education transformation toward a more just, sustainable, and peaceful future.

This brief, highly readable volume fills a critical gap in efforts to make scientific insights both accessible and meaningful for educators and policymakers. Coch and Daniel don't just bridge the gap between neuroscience and education; they show us how to cross it responsibly. This is essential reading for anyone who is serious about using research to improve teaching and learning.

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Education is among society's most important endeavors, and teachers face the enormous challenge of managing their work amid changing social contexts and ever-evolving cognitive and learning science that may or may not apply to the classroom. In this concise volume, Coch and Daniel provide a powerful framework that focuses on HOW to think rather than WHAT to think about scientific studies of learning and the brain. They equip educators to critically evaluate research to determine its classroom relevance. I recommend this insightful and practical guide for all educators, current and future.

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ISBN 978-90-04-73529-3
9 789004 735293

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