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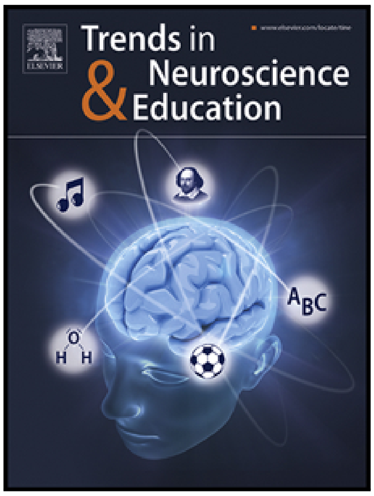

Three Pillars of Educational Neuroscience from Three Decades of Literature

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REVIEW ARTICLE

Three Pillars of Educational Neuroscience from Three Decades of Literature

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Abstract (120 words)

An on-going challenge for educational neuroscience is in defining the field, particularly in relation to the broader fields of education, psychology and neuroscience. The field is rapidly growing; the number of papers published under search terms "neuroscience and education" has skyrocketed in recent decades with various viewpoints debated. As interest expands to teachers, policymakers, and the popular media, the answer to "What is educational neuroscience?" becomes increasingly important. We approached this question through a systematic review of the literature and thematically analyzed all reported definitions and mission statements with three major themes emerging: application, interdisciplinary, and translation of language. This review discusses how these pillars have served as a foundation for the field and must support its future growth.

Keywords: *educational neuroscience; neuroeducation; mind, brain, and education*

1. Introduction

In 1985, the idea of a “neuroeducator” was posed by Jocelyn Fuller and James Glendening. These authors considered the development of a field of science that would be interdisciplinary in nature and that would highlight the importance of good teaching by utilizing knowledge of brain structure and function. The “neuroeducator” would have a place in schools and a place in the laboratory after thorough training in disciplines relating to psychology, neuroscience, and learning sciences [1]. Since the appearance of this term in 1985, there has been a soaring interest in the role of neuroscience in education [2] paralleled by an explosion of discoveries, innovations, and breakthroughs about the brain from institutes across the world.

One of the most widely discussed consequences of what has been called The Golden Age of Neuroscience [3] is its infiltration and impact across disciplines, particularly the social sciences. The implications of human brain research for education, in particular, are far reaching. New discoveries of child brain development, including the cognitive networks and contexts underlying learning and motivation have the potential to revolutionize school systems across the world [4]. Dozens of institutes and programs have been formed in recent years [5], with the goal of promoting crosstalk among educators, psychologists, policy makers, and neuroscientists. Many of these programs offer workshops, certificates or graduate degrees dedicated to translating discoveries about the brain to help students learn (see Appendix A: supplementary material).

This burgeoning field is called educational neuroscience, or in some circles, neuroeducation or Mind, Brain and Education. The development of the field has been intensely discussed and debated by multiple scholars [6-9]. Some of the earliest debates suggesting that the field is a “bridge too far” originated from misunderstandings of what *is* educational neuroscience, what is its mission, and what is the gap that this mission fulfills [9] (see section 4.1). As Howard-Jones and colleagues rebut, educational neuroscience is not just a way to improve, explain or analyze teaching, but is far broader; it seeks to explain how students learn and how learning changes the brain and then apply these findings to into the classroom [9]. Indeed, to define an interdisciplinary field that involves many perspectives and areas of expertise is challenging, and the answer to "What is educational neuroscience?" or "Who is a neuroeducator?" can still be misconstrued. To address this question, we performed a systematic and comprehensive literature review and thematically analyzed all reported definitions and mission statements with three major themes emerging. In this paper, we review how these three themes have served and continue to serve as foundation pillars for the field; we discuss the debates and controversies surrounding them, and we propose how they support future growth of the field. We aim to be clear that the goal of this review is not to argue for or against the potential of educational neuroscience, which has been done exceptionally well in previous works [6, 7, 10-16]; rather, the goal of this work is to characterize the thematic foundations of the field, as represented by the literature.

2. A Thematic Analysis of Educational Neuroscience

Three electronic databases, PubMed, OVID PsychInfo and ERIC, were searched in the summer of 2017 using the following search terms: "Educational Neuroscience", "Neuroeducation", "Neuroeducator", Mind Brain Education", and "Mind Brain and Education" (Figure 1). Hand searches of bibliographies were also conducted. Articles were screened according to the following inclusion criteria: (1) published in English, (2) published in peer-refereed journals, (3) contained relevant titles that met title filtering criteria (see Figure 1), and (4) contained an explicit definition, goal statement, or mission statement of at least one of the search terms within the article. Papers categorized as original paper, original research article, article, theoretical note, review article, report, opinion article, commentary, perspective, editorial, or overview were included. Literature sources categorized as book reviews, editor's introductions to special edition journals, and comment forums were not included. This resulted in a total of 64 articles with definitions that were thematically analyzed (Figure 1; see Appendix A: supplementary material). These articles represent publications from 38 different peer-reviewed journals published over the last 30 years (1985-2017) by researchers at institutions from 19 countries: Argentina, Australia, Belgium, Brazil, Canada, Chile, France, Germany, Greece, India, Italy, Japan, Netherlands, New Zealand, Portugal, Switzerland, Turkey, United Kingdom, and the United States. The definitions and/or mission statements from these papers were qualitatively and thematically analyzed as outlined by Elo and Kyngas [17]. Each definition in the literature fell broadly into one of three major themes: definitions that focus on the application of neuroscience into the classroom to improve educational practice, definitions that focus on collaboration or integration of multiple disciplines, and definitions that focus on bridging or translating language from different disciplines (Figure 2).

3. Three Emerging Themes

3.1. The Application of Neuroscience to Classroom Learning

The first major theme characterized in definitions and mission statements of educational neuroscience is application [18]. The focus of these definitions is the *application* of discoveries about the brain to the classroom or the use of neuroscience to *inform* innovations in education and direct novel approaches to teaching. Definitions and mission statements within this theme included the key terms: advance, apply, enhance, improve, inform, and understand (Figure 2A). A total of 37 of the 64 articles (58%) used defining words along this theme (Table 1 and supplemental material). According to this theme, educational neuroscience is unlike other related fields, such as cognitive neuroscience, because it extends beyond the basic sciences and into the social and applied sciences [19]. The key is that the impact of educational neuroscience is not merely in discoveries made but in its potential to "[improve] educational practices" [20]. In this respect, it has often been called a translational science.

Commonly discussed applications of neuroscience into the classroom include reading, language, numeracy, attention and memory, as well as the effect of emotion, stress, and sleep on neuroplasticity. One specific (and successful) example of an educational neuroscience discovery with concrete application to the classroom comes from work by Rivera and colleagues [21]. This study determined that younger students utilize different brain regions to learn arithmetic compared to older students. Specifically, younger students require additional working memory and attention areas to attain the same level of arithmetic competence as older students. Because older students lack activation in regions used by younger students, it is suggested that as children grow, they depend less on working memory and attention when solving math problems [21]. Unfortunately, a teacher cannot see when and where a particular student's brain is activated while performing arithmetic to gauge working memory. However, the conclusions drawn from this study *can be applied* into the classroom strategically if teachers provide skills training for younger students to help them improve working memory and attention, in parallel to (or prior to) lessons on arithmetic. Bowers claims that a shortcoming of educational neuroscience is that it merely informs behavioral methodologies [7], but Howard-Jones and colleagues claim that this is a necessary component of educational neuroscience—techniques like neuroimaging and electroencephalography (EEG) can help to inform new methods, but they need to be evaluated based on their effectiveness in behavioral contexts [22]. Thus, the application of neuroscience discoveries directly to the classroom can be conceptualized here as both necessary and important.

3.2: An Interdisciplinary Collaboration

A second theme found in mission statements and definitions of educational neuroscience is “the interdisciplinary collaboration” in which the whole is greater than the sum of parts. Key terms found within this theme include: integrate, interdisciplinary, join, collaborate, blend, bring together, work together, synergy, combine, merge, and overlap. A total of 39 of the 64 articles analyzed (61%) used defining words along this theme (Table 1 and supplemental material).

The Venn diagram is often used to represent symbolically the interdisciplinary collaboration that is considered critical for the field with contributions from neuroscience, psychology, and education each representing one ring in the diagram (Figure 2, middle panel). Institutes such as the Center for Educational Neuroscience and the Royal Society, for example, highlight the importance of interdisciplinary work for the future development this field (see Appendix; also see [5] for a continuously updated list of labs associated with the field). Ansari and colleagues claim that such interdisciplinary work provides for a smooth transition between various disciplines and encourages multi-level analysis to answer difficult questions [23]. Promoting interdisciplinary studies among neuroscience and education enables educators to ask neuroscientific questions and enables neuroscientists to ask educationally-relevant questions [23]. Carew and Magsamen note that our world is different than any other time in history—there are new technologies and new innovations that can lead to better learning, and parents and educators want access to these methods to help their children succeed now more than ever [24]. A prime example of successful interdisciplinary collaboration is a study conducted by Neville et al., whose group utilized principles of neuroplasticity to design a family-based training program for at-risk preschool students that helps them to develop skills in attention both in the classroom and at home [25] (Box 1). This study involved experts from many fields including psychology, neuroscience, education and social work, as well as parents, teachers and students as illustrated schematically in Figure 3.

3.3: A Translator of Languages

A third theme found in definitions and mission statements of educational neuroscience is the *translation of languages*, thought paradigms, and methods that have historically belonged to different disciplines. Definitions and mission statements along this theme maintain that the fields of neuroscience and education are distinct, but that educational neuroscience can help translate the languages used between the fields as a professional interpreter. Mission statements within this theme often include transportation imagery such as highways, bridges, and two-way streets (Figure 2, right panel) and include key words/phrases: translate, bridge, two-way, two-way street, transfer, and bi-directional. This theme was found in 16 of the 64 articles analyzed (25%).

While the bridge analogy is emphasized to be a “two-way street”, the lane running from neuroscience to education (i.e. the need to translate the technical language of neuroscience) is particularly emphasized in many discussions of the field [4, 18, 19, 26-38]. Neuroscience uses technical jargon and complex methods that are often unfamiliar to those outside of the scientific community; therefore, it is important to make the technical literature more accessible to educators who may not have had advanced training in the biological sciences. It is also critically important that neuroscience discoveries about learning and the brain are conveyed and communicated to educational policy makers. There are several examples of policy changes that have been attributed to educational neuroscience findings. Research in sleep, circadian rhythms, and the developing brain, for example, has prompted some administrators to adjust school start times (e.g. [24], see also reviews by Zadina [39] and Thomas, Ansari, and Knowland [40] for additional examples). Furthermore, numerous organizations and institutes have published educational neuroscience findings with efforts to inform the public (e.g. [12, 41-43]). This information is important for scientists and non-scientists alike.

Thus, individuals who can relay neuroscience information to educators are critical [10], but whether that responsibility belongs to educational neuroscientists or others is a topic of debate [10]. Furthermore, neuroscience methods are very different from methods used to study education; neuroscientists consider the brain as the main component involved in learning, but educationists examine the impact of various environments and settings on student learning (e.g. classrooms, home environment, playgrounds [44]. The Royal Society suggests that because of such a vast language barrier between scientists and teachers, relevant findings get misinterpreted, leading to neuromyths. Thus, some sort of forum or formal exchange should take place to connect teachers, researchers, and policy makers to ensure consistent and accurate translation of language [42]. This exchange will ultimately shape the field of educational neuroscience and will become a significant role of its practitioners [35].

4. Debates and Controversies

Like any emerging field, educational neuroscience has generated a flourishing array of debate and arguments regarding its efficacy. There are three broad categories into which the arguments for and against this field can be grouped: that the field is better (or already) approached by educational and behavioral psychologists; that the connection between neuroscience and education is too weak; and that the field is compromised by ‘neuromyths.’

4.1. Is Educational Neuroscience "Just a New Name for Cognitive Psychology"?

How does educational neuroscience differ from cognitive psychology or educational psychology? Cognitive psychology, according to the American Psychology Association (APA), utilizes experimental methods to study mental processes (e.g. learning) in order to modify behavior [45]. Similarly, the APA defines educational psychology as a field that uses theories of development to study how people learn, with an aim to influence instruction [45]. A criticism of educational neuroscience is that it seeks to establish a field and to answer questions that are best approached (or already addressed) by psychologists [6, 7]. These claims are somewhat defensible, as research in cognitive and educational psychology has contributed vast amounts of knowledge to the broader field of education. Both cognitive psychology and educational psychology produce behavioral data that impacts educational reform. In support of this, some scholars claim that behavioral measurements of learning performance, which can be collected by well-established psychological methods, are the most important outcomes by which to evaluate the effectiveness of instruction [7, 14], and that "observed brain changes may or may not have an impact on the relevant behavior" [7]. According to this perspective, neuroscience is neither needed nor relevant and has no place in education; thus, educational neuroscience is futile.

Rebuttals to Bower's criticisms of educational neuroscience state that Bowers' message "underestimates the scope of research in this new field and the complexity of interdisciplinary research spanning from neuroimaging centers to psychological labs to classrooms" [9]. This commentary by Howard-Jones and colleagues raises three major points that challenge Bower's criticism. First, Bowers provides no insight into the shortcomings of behavioral research, or how additional experimental approaches can bolster behavioral claims. Second, Howard-Jones and colleagues emphasize that educational neuroscience is not about competing with psychology—it is about collaboration and unity. Educational neuroscience cannot exist without behavioral research; the field of cognitive neuroscience already exemplifies how neuroscience and behavior can complement each other [9, 15].

Finally, Howard-Jones and colleagues explain how the debate is really a misunderstanding of terms, more specifically due to different definitions of educational neuroscience. Bowers' arguments surround an incomplete definition: that the only goal of educational neuroscience is to make teachers better at teaching through new instructional methods [7]. The fault here is that educational neuroscience seeks to do more than just develop novel teaching methods—it is also positioned to provide a way to improve student outcomes and lead to new discoveries about the brain and learning. Bowers reviews several educational neuroscience studies, claiming that their results are either trivial, misleading, or unwarranted. He notes how phonics, a behavioral method used to teach reading, is successful because it has been validated by behavioral and education research, not neuroscience [7]. If educational neuroscience is restricted to a definition that *only* includes behavioral studies of teaching methods (e.g. phonics), then there is no need for an interdisciplinary field; however, if educational neuroscience is defined in a way that incorporates interdisciplinary work and translation of language, then Bowers' argument falls short because it neglects the notion that neuroimaging data from phonics instruction enables researchers to look inside the brain at areas of interest and to understand *how* a student might actually learn via a novel tool. Thus, Bowers' arguments are understandable, but they collapse when a broader definition of educational neuroscience is applied.

4.2. Educational Neuroscience: "A bridge too far"

Another common critique of educational neuroscience is that it is a 'bridge too far' [16]; neuroscience cannot be applied to the classroom because teachers and students are unable to transfer neuroscience directly into useful educational practices [6, 7, 16, 46]. Bruer opposes the development of the field, asserting that the scientific community knows too little about neuroscience and how the brain develops to actually link it to classroom learning and teaching [16]. Bruer asserts that synaptogenesis and critical periods cannot directly inform educators how to teach students or what methods may actually benefit student learning. Bruer's ideas should certainly be considered, but it should also be noted that neuroscience research has progressed significantly since this article was published in 1997. In particular, significant discoveries have been made relating to synaptogenesis and critical periods of brain development. For example, while the brain is much more sensitive in the first few years of life to experiences that shape development (such as language and face recognition) we know that the brain is capable of changing through the entire lifespan and not just during critical periods [11, 47] (see also Chapters 6, 8, 10, 12 of [11]). Moreover, recent work in adult human hippocampus demonstrates that while neuroplasticity declines in aging in some areas of the hippocampus, other areas of the hippocampus display preserved neurogenesis throughout life [48] challenging other studies claiming that such neurogenesis is not preserved in the aging brain (e.g. [49]). Nonetheless, conclusions drawn from research on neuroplasticity and classroom applications made based on this work must be approached with caution as described in a more recent discussion on this topic by John Bruer ([11]; see Afterword).

Horvath and Donoghue apply Bruer's work to argue that the field is unsustainable because neuroscience and education have "incommensurable levels-of-organization [46]."

Educationally-relevant neuroscience knowledge must first pass through a psychological interpretation before it can be applied to an educational setting to help students and teachers. Because educational effectiveness is measured on a behavioral level, neuroscience can only inform the psychology of learning, which in turn informs behavior and, thus, education [46]. Others suggest, however, that direct paths from neuroscience to education can be made; for example, suggest the impact of metabolism, exercise, nutrition, stress hormones, or environmental pollutants on brain function (including learning) can be examined without psychological approaches or interpretations [40]. Nevertheless, as emphasized in Figure 2b and 3, the field is interdisciplinary; there is neither an institute nor educational program dedicated to educational neuroscience that establishes a program based entirely on one discipline [5]. The field of educational neuroscience should integrate behavioral research, education research, and neuroscience research (Figure 2b). Educational neuroscience programs and institutes are not created to replace psychology or other related fields—rather, they are created to train practitioners that can communicate within and use methods from multiple disciplines with the utmost goal of advancing research, informing educational policy makers, and improving student learning. Thus, perhaps the third pillar, "translation of language" (Fig 1c) cannot exist without the second pillar of interdisciplinary collaboration (Fig 1b).

Box 1

Educational Neuroscience at Work: A Prime Example

A study conducted by Neville and colleagues provides a prime example of the interdisciplinary collaboration uniquely characteristic of educational neuroscience and exemplifies the fundamental contributions from fields of psychology, neuroscience, and education. In brief, the authors utilized an eight-week training program aimed at helping preschool children from lower socioeconomic statuses to be more successful in school. The program was oriented to target selective attention. The novelty of this study rests in the authors' ability to integrate the fields of multiple disciplines: psychology, neuroscience, and education. The authors determined a behavior (attention) that is relevant to education, psychology, and neuroscience. Psychological methods were used to examine the behavior itself and how it changed based on intervention, and neuroscience methods (event-related brain potentials) were used to measure the change in behavior at a neural level. Research findings in neuroscience also helped to motivate the intervention, as the authors utilized previous work on the neuroplasticity of attention as rationale for their study. (Figure 3). The study involved psychologists, neuroscientists, teachers, and parents, who all shared a common objective: to improve the educational outcome of students [25]. Thus, successful examples of educational neuroscience in practice, such as this one, illustrate the point that educational neuroscience should not replace psychology-related disciplines or even neuroscience-related disciplines but instead stand upon the shoulders of these giants and add to them using advanced neuroscience technologies to peer into the active human brain.

[Insert Figure 3 Here]

4.3 Educational Neuroscience: "A Producer and Perpetuator of Neuromyths"

Neuromyths, a frequently used neuroscience colloquialism, are considered another common critique of educational neuroscience because they lead to false perceptions of neuroscience research. In actuality, these myths can actually promote the study of educational neuroscience, as they captivate the interest of students, parents, and teachers and encourage them to think about how the brain works. An analysis of neuromyths has been conducted in various reviews [10, 50, 51], and some of the most ubiquitous of these myths include: that humans only use 10% of their brain; that some people are right-brain dominant or left-brain dominant; and that children are best taught certain skills during a ‘critical period’ of development.

Michael Ferrari claims that caution must be taken when educators approach neuroscience; educators may accept neuroscience facts regarding their teaching practice even though said facts do not explicitly add substance to the material being used or to the lesson being taught [52]. The addition of irrelevant neuroscientific explanations to descriptions of psychological phenomena made them more satisfying to non-experts and even made what were considered ‘bad-explanations’ sound viable to these non-experts [53, 54]. Neuromyths spawn from challenges in the *communication* of educational neuroscience, rather than the validity of the science itself; such communication challenges are not unique to educational neuroscience, but common to all translational or applied sciences that engage multiple disciplines. Moreover, neuromyths highlight the need for educational neuroscientists to ensure false claims about neuroscience are not promoted; their incidence ought to motivate scholars to ensure that neuroscience is not used to promote unrelated educational information in classrooms simply because it ‘sounds good’

As demonstrated above, there is certainly evidence to support how neuromyths can detract from the aims of education by incorporating false neuroscience claims; however, neuromyths can also be used to support the foundation and growth of educational neuroscience. Several authors claim that we should use educational neuroscience itself to counter neuromyths that lead to ineffective or unsupported instructional methods (e.g. right brain/left brain and learning style [50, 55, 56]. This can be achieved by suggesting that educators have access to training in basic neuroscience or scientific methods [26, 31, 41, 42, 56-60]. This training could empower teachers with the knowledge to refute and dismiss neuromyths, which would prevent them and other teachers from adopting ill-researched methodologies in the classroom [56]. Additionally, practitioners of educational neuroscience could educate teachers and school administrators and policy makers as to what is supported by research and what is really a myth [55, 61]. A good example of educational neuroscientists doing just this comes from the Centre for Educational Neuroscience [61].

The appeal of neuroscience presents a challenge to developing educational neuroscience because of neuromyths, but it also illustrates the high interest level among teachers, students, and parents in understanding how to learn best and most effectively. An article published by the Public Broadcasting Service (PBS) describes neuromyths and their pervasiveness in classrooms and how educators constantly use methods that can detract from and even hinder learning. Regarding the neuromyth of learning styles (e.g. visual, auditory, kinesthetic), the authors claim that this practice leads to students neglecting other learning modalities, as the students are taught based on their preferred style of learning [62]. Others claim that it is a mistake to use educational neuroscience to refute neuromyths because neuroscience is exploited in the education arena and becomes sensationalized; thus, any type of neuroscience related to education is 'meaningless' [7]. However, when we consider the potential of neuroscience to actually inform the public in realms such as language development, literacy, mathematics, and social and emotional development, there is substantial promise. There have been several significant bodies of work published in the last several years that have summarized the promise of educational neuroscience in each of these areas [e.g. 10, 11, 12, 13].

Relating to the appeal of neuroscience, it should be emphasized that teachers are generally receptive to learn about neuroscience and apply it in the classroom. Several studies and surveys have been conducted that evaluate overall perceptions of neuroscience as it relates to education among teachers, education researchers, and neuroscientists [58, 63-65]. Importantly, one study found that teachers commonly use very broad definitions of educational neuroscience that extend into research that would properly be called cognitive psychology or educational psychology [58]. Within the population sampled, teachers also seem to have a genuine interest in the brain as it relates to teaching and learning and are interested in more than just acquiring new instructional methods [58]. A study conducted by Pickering and Howard-Jones found that teachers in the UK have a devoted interest in learning about the brain, but they want it to be accessible and relatable to their profession [63]. An article by Bruno della Chiesa et al. discusses the challenges faced by the Organization for Economic Cooperation and Development's report on *Learning Sciences and Brain Research* project, highlighting that, while educational researchers and neuroscientists seemed hesitant to accept findings and to engage in open, interdisciplinary dialogue, actual teachers and practitioners were much more open and encouraged by the open-dialogue. It is suggested that the reason for this is because, aside from students, teachers are the most impacted by the potential benefits educational neuroscience [64]. Conceivably, what is important to recognize here is that educators seem to be invested in the promising implications of educational neuroscience, and they should have a significant voice in the development of the discipline.

5. Future Directions and Recommendations

Perhaps one of the most curious topics neglected in the literature is the perspective of those it aims to affect most: students. In particular, none of the 64 articles analyzed in this systematic review investigated the opinions or perspectives of students who have been impacted by or learned about educational neuroscience in the course of their education; this is an important goal for future studies. What do students think of this field? What do they see as its potential?

What do they want from the field? As the field continues to grow, there is a need for more studies that examine student perspectives, opinions and desires of the field. Moreover, we suggest that definitions and mission statements of educational neuroscience not only incorporate the three pillars revealed by the last 30 years of literature (application, interdisciplinary, and translation of language) but that they also include a focus on learners. We suggest a working definition in Box 2:

Box 2

Educational Neuroscience: An Integrated Definition Incorporating the Three Themes

The integration of education, psychology, and neuroscience into an interdisciplinary field that is devoted to helping students learn. Educational Neuroscience communicates the language of multiple disciplines and applies methods from multiple disciplines to translate discoveries about the brain and its networks into educationally relevant outcomes.

The three pillars discussed in this review are recurring themes in the educational neuroscience literature over the last 30 years and have been foundational to the development of the field. However, weak spots exist; we offer some recommendations to fortify and strengthen these pillars:

1. <u>Application</u>: Neuroscience discoveries are oftentimes ignored or overlooked by important educational decision makers and stakeholders. To induce change, they must be applied to the classroom. A prime example of this surrounds the debate regarding the use of computer screens and tablets in classrooms. Many neuroscientists and psychologists have concluded that digitalizing classrooms is not a guaranteed way to improve learning. Instead, these devices can actually have negative impacts in the classroom, where these devices can inhibit neuroplasticity, lead to addiction behavior, distract classmates, and

lead to lower performance on exams [66-70]. Yet, these devices are marketed to schools as a means to improve learning and to resuscitate suffering school systems without evidence from the literature. We do not mean to suggest that digital devices necessarily be excluded from the classroom; instead, we entreat that the incorporation of digital devices be designed and used strategically – at the proper time and to meet the proper learning goal - based on evidence, so that it improves, not inhibits, learning. To achieve this goal, it is imperative that more research is performed to understand the effect of digital devices on the student brain, not merely behavioral measures of student performance, and that this information is applied to the classroom and conveyed to educational stakeholders. The use of tablets in the classroom is only one example, but these guiding principles for effective application can be extended to many examples, including the use of "brain training" products [71] or other popular strategies designed to improve cognition or learning (reviewed in [39, 40]).

2. <u>Interdisciplinary collaboration</u>: This review has emphasized how collaboration between educators, psychologists and neuroscientists is a crucial pillar for the field of educational neuroscience. There are many examples of interdisciplinary teams collaborating effectively (see Box 1 and Appendix). However, there are perhaps too many examples in which practitioners have remained in silos or have argued over territory, ownership, or objectives [6-9]. We hope the three pillars described here provide a unifying vision that motivates scholars from all disciplines; moreover, the advancement of serious interdisciplinary research programs in educational neuroscience such as those referenced in Table 1 (in Appendix) will produce more and more examples of the successful applications, collaborations and translations between neuroscience and education to spur

progress in the field (e.g. [11, 12, 30, 40-42, 52]). Beyond these goals, we suggest that interdisciplinary collaboration should expand beyond the disciplines of education, psychology and neuroscience to also include medicine, law, business, science and technology. The majority of research in educational neuroscience has been focused on elementary education, but there is a great potential for the field to impact how we train adult students, including medical students, doctoral students, law school students, and business students. Many of these adult training programs include learning environments of great stress, intense competition, high stakes endurance testing (board exams or the bar exam) and severe sleep deprivation (i.e. medical resident training), all relatively untouched areas of educational neuroscience research.

Medical schools across the United States, as a particular example, continue to undergo curricular change, reorganization, and reform in a response to accreditation mandates for more self-directed learning experiences, self-assessment opportunities, and advanced technology resources to help students develop core clinical competencies [72]. In response, medical educators seek new approaches to teaching such as flipped classroom, team-based learning, case-based learning and new educational technologies. Virtual reality simulation, haptic simulators, wearable devices (google glass), mobile apps, podcasts and videos are being explored as ways to facilitate basic knowledge acquisition, skill coordination, decision making skills, and practice for clinical events [73]. These innovations require large investments of finances and faculty time; yet, as in the case of tablets mentioned above, there is little evidence to support their validity and reliability (e.g. [74]). Most studies are anecdotal and very few investigate the impact of such technologies on neural networks in the brain (see [75] for one research study performed in the context of patient education). There is a prime opportunity for educational neuroscientists to address questions related to the use of advanced educational technologies in the graduate learner and the adult brain. How do virtual reality educational interfaces impact neural networks in medical trainees (and how might this differ compared to the use of these technologies in the developing brain of the elementary or adolescent learner)? Do these technologies impact long term retention or clinical decision making? What types of educational goals are best met via these advanced technologies and which are better met with traditional didactic approaches? At what stage in a student's training are these best introduced? What can these educational innovations teach us about how the brain learns?

3. Translation of Language: The first two pillars of educational neuroscience listed above depend on effective translation of discipline-specific language. Thus, there is a need for more translators who can speak the language of both education and neuroscience. Furthermore, there is a need for more funding for training programs like the ones listed (see Table 1 in Appendix) dedicated to creating scholars trained in multiple disciplines who can do the hard work required of the first two pillars.

6. Conclusions

Our work reveals that the field of educational neuroscience over the last 30 years has been defined by three major themes that include application, interdisciplinary collaboration, and translation of language. These themes have served as foundational pillars for the field and support its future growth. Educational neuroscience should not replace psychology-related disciplines or even neuroscience-related disciplines but should, instead, stand upon the shoulders of these giants and add to them using the advanced technologies and methodologies offered by neuroscience to explore and understand the brain. Importantly, it is worth emphasizing that educational neuroscience seeks to help students—its aims should encourage students to understand how they learn best so as to minimize imbalanced difficulties in the classroom and to promote achievement throughout life.

7. Author Contributions

JBF conducted the literature review and analysis. MES provided study design and supervision. Both authors wrote and revised the manuscript.

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Table 1

*Themes found within published definitions and mission statements of educational neuroscience**

Theme	Code Words	Citations that include code words	Total # (%) of Articles
Application	Advance Apply Enhance Impact Improve Inform Understand	[1, 4, 7-9, 13, 18-20, 23, 24, 31-33, 35, 38, 50, 54, 76-95]	37 (58%)
Interdisciplinary Collaboration	Blend Bring-together Collaborate Combine Integrate Interdisciplinary Join Merge Multidisciplinary Overlap Synergy Transdisciplinary Work-together	[1, 4, 13, 18, 20, 24, 26, 27, 29, 30, 44, 50, 52, 54, 57, 78, 81, 83, 85-87, 89, 91, 92, 95-109]	39 (61%)
Translation of language	Bidirectional Bridge Transfer Translate Two-Way Two-Way Street	[4, 18, 19, 26-38]	16 (25%)

**Note*. Total number of articles analyzed was 64. Note that 27 of these (42%) had definitions or mission statements that fit within two or more themes (see also Appendix).

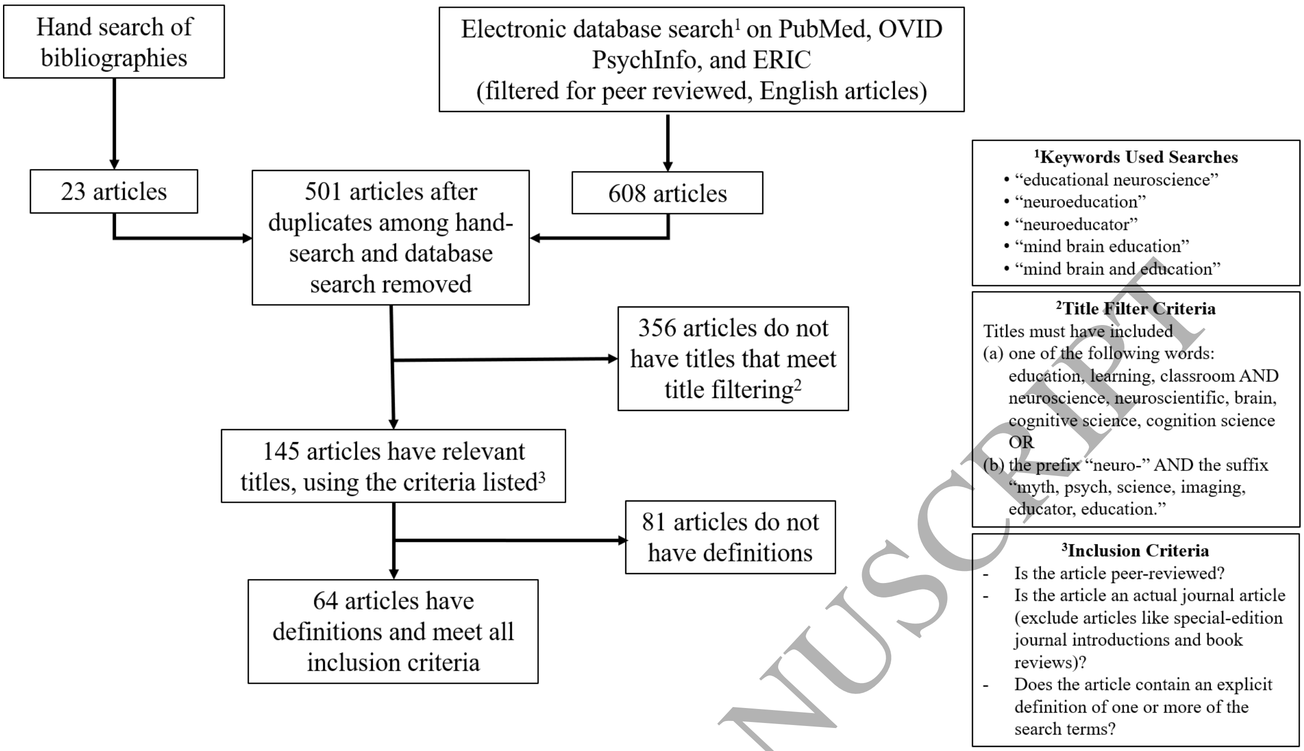

Figure 1. Flow chart of the systematic approach used to analyze articles for definitions/mission statements.

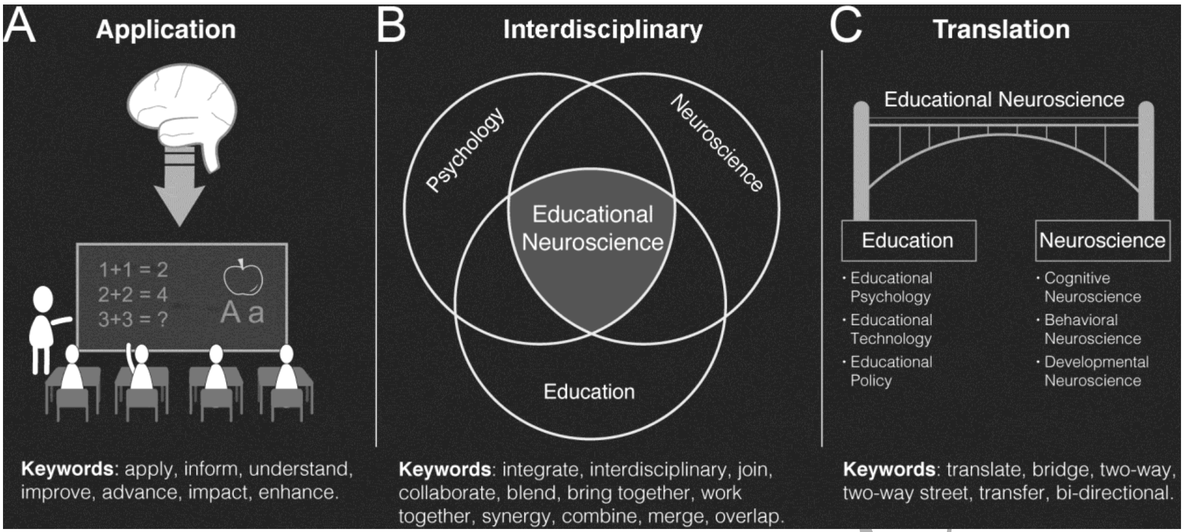

Figure 2. Visual depictions of the three major themes of found within mission statements and definitions of the field of educational neuroscience: (a) application of neuroscience discoveries into the classroom, (b) overlapping and interdisciplinary collaboration of psychology, neuroscience, and education, and (c) a bridge that translates technical languages and jargon between education and neuroscience.

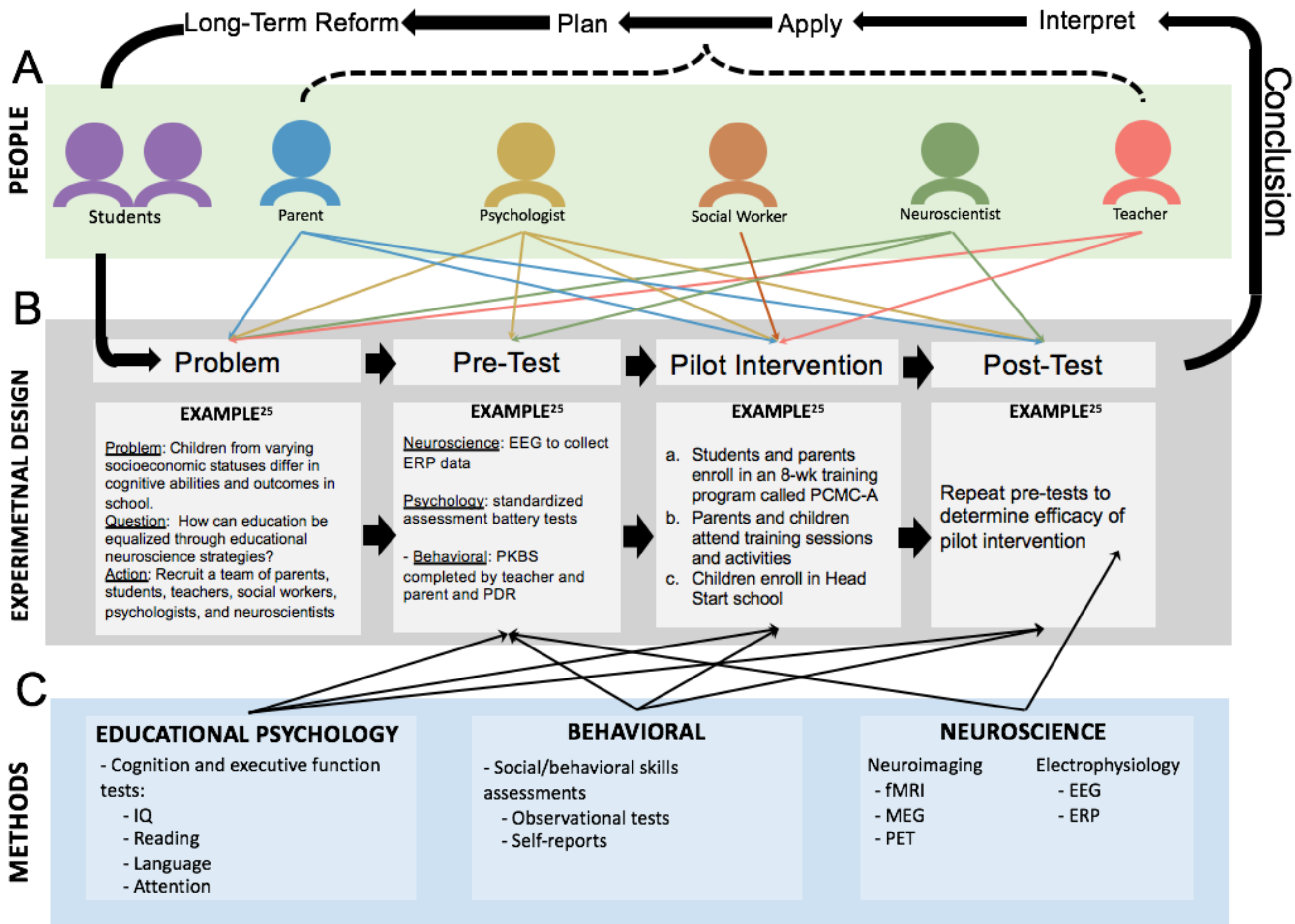

Figure 3. A sample model of educational neuroscience collaboration in practice (A) Students, teachers, parents and experts form the fields of psychology, neuroscience, and education contribute the diversity of participants in successful educational neuroscience research. Colored arrows point to each person's role in various components of the research which creates a complex web-like structure characteristic of fruitful multidisciplinary collaboration. (B) A sample experimental design model for an effective educational neuroscience includes: the identification of a problem, recruitment of a team of scholars from various disciplines, pre-test, intervention, post-test, and conclusions which initiate the process of educational reformation. Recent work by Neville and colleagues [25] can be used as a model for implementing

multidisciplinary research (C) A sampling of methods from each of the three disciplines involved in educational neuroscience and how they can be applied to each part of the experimental design. IQ – Intelligence Quotient; fMRI – Functional Magnetic Resonance Imaging; MEG – Magnetoencephalography; PET – Positron Emission Tomography; EEG – Electroencephalography; ERP – Event Related Potential

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