MIND, BRAIN, AND EDUCATION

A Place for Neuroscience in Teacher Knowledge and Education

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ABSTRACT— The foundational contributions from neuroscience regarding how learning occurs in the brain reside within one of Shulman's seven components of teacher knowledge, Knowledge of Students. While Knowledge of Students combines inputs from multiple social science disciplines that traditionally inform teacher education, teachers must also (and increasingly) know what happens inside students' brains. Neuroscience professional development provides neuroscience principles that teachers can learn and apply to distinguish among pedagogical choices, plan lessons, guide in-the-moment classroom decisions, and inform the views of students. Neuroscience does not directly invent new pedagogies. Rather, knowledge of neuroscience guides teachers in choosing appropriate pedagogies, pragmatically informing teaching. By providing physiological explanations for psychological phenomena relevant to education, teachers benefit from neuroscience content in their training and professional development.

Recent decades have brought unprecedented growth of mechanistic knowledge of how the human brain functions to create behavior and drive thinking and learning. Nevertheless, the idea that neuroscience might contribute to teacher education faces strong resistance (Bowers, 2016). Even among those acknowledging a connection, the question of where in teacher competency, preparation, and practice neuroscience belongs remains debatable (Ansari, Konig, Leask, & Tokuhama-Espinosa, 2017). Potential applications of neuroscience to teacher education range from the technical, such as providing biomarkers for learning progressions, to the theoretical, such as distinguishing between learning theories (Howard-Jones et al., 2016). For example, functional near-infrared spectroscopy of teacher-student interactions has been used to identify pedagogies where learning correlated with interpersonal brain synchrony (Pan et al., 2020). However, many experimental findings remain far removed from teachers' daily practices, causing them to be challenged as epistemologically distant, futuristic, or irrelevant (Bowers, 2016; Dougherty & Robey, 2018).

William James pioneered the pragmatic point of view, which is that the utility of an idea is what determines its truth and operational relevancy (Berliner, 2006). To become relevant for education, neuroscience must have practical applications for teachers (Clement & Lovat, 2012). This is an appropriately high bar. The neuroscience ideas pertinent to student learning and teacher pedagogy have been enumerated previously (Deans for Impact, 2015; Dubinsky, Roehrig, & Varma, 2013). Understanding the biological basis for learning and memory and how this is modulated by stress, sleep, emotions, experiences, exercise, and the food and drugs one ingests is relevant for guiding teachers' pedagogical choices in the context of their classrooms (Deans for Impact, 2015). Indeed, recent studies have demonstrated that neuroscience knowledge *is* useful for teachers, justifying its application in education (Dubinsky et al., 2013; Owens & Tanner, 2017). Teachers utilized neuroscience as a framework to guide both planned and in-the-moment pedagogical decisions and as a lens on student capabilities (Brick et al., 2021b; Chang, Schwartz, Hinesley, & Dubinsky, 2021; Friedman, Grobgeld, & Teichman-Weinberg, 2019; Tan & Amiel, 2019). PD experiences around neuroscience also improve teacher competencies of self-efficacy, motivation, self-regulation, and self-responsibility for student outcomes (Brick et al., 2021b), as well as positively impacting teachers' student-centered pedagogical practices (MacNabb et al., 2006; Roehrig, Michlin, Schmitt, MacNabb, &

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Dubinsky, 2012; Schwartz, Hinesley, Chang, & Dubinsky, 2019). Given these demonstrated practical applications of neuroscience in classrooms, this paper asserts that neuroscience knowledge should become a part of teacher preparation and professional development programs. This paper addresses the central question: *Where does neuroscience fit in teacher knowledge?* Answers to this question have been informed by examining the benefits of neuroscience to teachers' pedagogical decision-making and views of students.

Shulman's seminal model of teacher professional knowledge provides a useful starting place (Shulman, 1986, 1987). Shulman (1987) described teachers' knowledge as falling into seven categories: content knowledge, general pedagogical knowledge (PK), pedagogical content knowledge (PCK), curricular knowledge, knowledge of students (KoS) and their characteristics, knowledge of educational systems and contexts, and knowledge of educational theories and philosophy. KoS includes KoS' abilities and learning strategies, ages and developmental levels, attitudes, motivations, and prior knowledge of the concepts to be taught (Shulman, 1987). Shulman (1998) drew on Dewey's original writings arguing for the inclusion of psychology in teacher education, at which point in time the nascent field of psychology was the most advanced approach to understanding learning. Neuroscience was not a separate field in Dewey's lifetime. However, neuroscience knowledge can provide insights into how learning takes place in the brain and what physiological, affective and motivational states contribute to optimal student learning; this is KoS. Shulman (1986) argued for teacher education to follow a professional model, comparable to the medical and legal fields, which includes constantly updating the foundational knowledge needed by professionals in the field. Similarly, Hoy (2000) challenged 21st-century educational psychology to update its theories to enable teachers to better promote student learning. Neuroscience, as part of KoS, satisfies this call, and should therefore become a fundamental part of teacher education and professional development. Thus, this paper argues the neuroscience of learning and memory should be viewed as an essential part of KoS and examines how neuroscience, as part of KoS, acts as a filter to influence teachers' views of students and choices of pedagogies from among their own PK.

Conceptual guidance for locating neuroscience within teacher education is provided by Pasteur's Quadrant (Stokes, 1997). In classifying research endeavors for policy analysis, this framework organizes research along two axes, a search for fundamental understanding versus consideration of use (Stokes, 1997). Pasteur's work combines both, uncovering new knowledge and applying it for practical uses. Educational psychology can be similarly situated within Pasteur's Quadrant, applying the results of psychological research to education (Berliner, 2006). Perhaps surprisingly, neuroscience fits equally well in Pasteur's Quadrant (Sigman, Peña, Goldin, & Ribeiro, 2014). Within Educational Neuroscience (Figure 1), knowledge gained from multiple disciplines, using multiple methodologies to collect biological and behavioral data, is applied to understand the effectiveness of educational approaches (Howard-Jones et al., 2016). Thus, Sigman et al. (2014) argue for a *physiological foundation for pedagogy*. From their perspective, both educational psychology and neuroscience combine basic research into behavior and the biological basis for that behavior with the application of this research in education (Berliner, 2006; Sigman et al., 2014).

Educational researchers have built on Shulman's work, offering multiple re-conceptualizations of the contribution of KoS to teacher knowledge and practice (Appendix, Table 1). Conceptions of KoS vary greatly (Appendix, Table 1). These include viewing KoS as part of learning theories (Barnett & Hodson, 2001), as a component of PK (Dohrmann, Kaiser, & Blomeke, 2012), as an understanding of cultural backgrounds (Allen, Hancock, Starker-Glass, & Lewis, 2017), and as learning how students respond in classrooms to particular content, PCK (Ball, Thames, & Phelps, 2008). Many of these newer views of teacher knowledge only focus on its cognitive dimensions, eliding the neural underpinnings. For example, Schoenfeld and Kilpatrick (2008) break KoS into the knowledge of student thinking and KoS as learners. This analysis does not address any of the physiological variables that might influence current contexts or cognition; rather, it is exclusively about thinking processes and behaviors. A more nuanced view is offered by Voss, Kunter, and Baumert (2011), who integrate the knowledge of individual student characteristics (KoS) within teachers' *general pedagogical and psychological knowledge*. These characteristics include students' cognitive, emotional, and motivational abilities, with the cognitive abilities further broken down into learning, memory, attention, information processing, and cognitive development. This finer-grain analysis leaves hooks for relevant neuroscience concepts. For example, synaptic plasticity provides the basis for learning with memories stored in and recalled from the set of synapses associated with the learned object, skill or experience (Kandel, 2009). In addition, an emerging understanding of the dynamics of brain networks potentially informs attention, information processing, and cognitive development (Bassett & Mattar, 2017). Thus, Voss's framework has the virtue of offering a potential role for neuroscience in teacher knowledge, specifically within KoS (Voss et al., 2011). If the tree of teacher knowledge has roots in a mix of disciplinary soils, neuroscience provides a key, previously missing nutrient: it supplies mechanistic explanations for the behavioral insights coming from other disciplines (Figure 1).

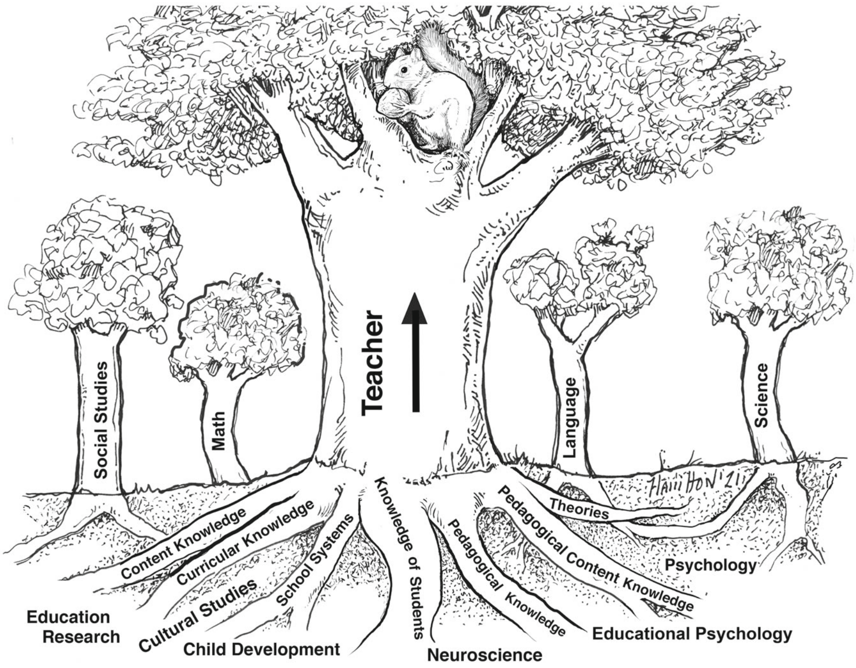

Fig. 1. The root ecosystem of a tree provides an analogy for providing teachers, represented as trees, with professional knowledge. The soil consists of nutrients provided by multiple research-based disciplines which become combined in pre-service education and professional development to become the categories of knowledge absorbed by the tree's roots. Neuroscience has become an integral, not always recognized, nutrient component of this soil. Teachers utilize and transform the combined knowledge (sap, arrow) into pedagogy to produce the nourishing environments of the bark and canopy. Creatures living in the tree's ecosystem represent students who benefit from the breadth of teacher knowledge (squirrel and nut). The combined fields of knowledge contributing to the richness of the soil have been variably termed Educational Neuroscience, Science of Learning, and Mind, Brain and Education (Fischer, Goswami, & Geake, 2010; Meltzoff, Kuhl, Movellan, & Sejnowski, 2009; Schwartz, 2015). Image credit: William P. Hamilton, CMI.

Inclusion of neuroscience within KoS is a less radical proposal than might first seem to be the case. Among the various types of teacher knowledge, Shulman (1986) states that "aspects of physiology are apparently deemed necessary because of the expectation that teachers understand the biological functioning of their pupils" (p. 5). Subsequently, developmental and cognitive science have described the capacities of growing children in scholastic contexts (Posner & Rothbart, 2007). Development, writ large, spans from physiological to associated behavioral changes. Theories of the professional knowledge that teachers need to know, including the fundamental mechanisms of developmental science and neuroscience, have all evolved. These fields have progressed in parallel, with inconsistent interactions between education research and scientists. The contemporary convergence of these overlapping fields warrants the inclusion of neuroscience as a critical component of teacher knowledge.

Neuroscience provides physiological knowledge of learners and their characteristics–provides KoS–and thus belongs within teacher education programs. But KoS is itself a broad term. This paper considers where neuroscience belongs within KoS. In doing so, it first reviews the complementary views of KoS emanating from the fields of neuroscience, educational psychology, and educational research. Next, data from programs that have documented how teachers utilize newly acquired neuroscience concepts in their practices are presented to document the benefits of this knowledge. These provide empirical evidence that a rapprochement of neuroscience and teacher knowledge is both possible and beneficial. Lastly, the relationships among KoS, neuroscience, PK, and learning theories are briefly discussed. In this discussion, we promote the idea that neuroscience content appropriate for education should be incorporated into both teacher preparation and professional development but leave such implementation details for further discussion.

KNOWLEDGE OF STUDENTS IS GENERATED FROM MULTIPLE SCIENTIFIC DISCIPLINES, INCLUDING NEUROSCIENCE

KoS as a broad category of teacher competence has many potential components. It has typically been concerned with developmental descriptions and theories of changes during childhood (Posner & Rothbart, 2007). Behavioral explanations of growth in cognitive capacity have been carefully documented by developmental and educational psychologists (Goswami, 2019). Educational researchers have debated and redefined KoS from both theoretical and practical perspectives (Appendix, Table 1). KoS ranges from beliefs about how students think (Schoenfeld & Kilpatrick, 2008) to a set of six principles connecting the cognitive neuroscience of student learning to classroom applications (Deans for Impact, 2015).

Neuroscience brings biological, mechanistic explanations for many of the previously identified components of KoS (Diamond & Amso, 2008). Different brain circuits and regions mature and grow at different rates with both age and experience. A teachers' understanding of cognitive development can be strengthened with additional background on the biological mechanisms-the development of the connections between neurons, the growth of new neurons, and the formation of myelin around the axons of neurons that increase their speed of operation by an order of magnitude-that undergird those cognitive changes. The development of neural networks during the preschool years, their growth during the elementary years, their restructuring during adolescence, and refinement into adulthood are differentially influenced by both genetic and environmental factors (Silbereis, Pochareddy, Zhu, Li, & Sestan, 2016).

Regarding preparation for learning, KoS also includes comprehending learners' intuitive notions about different academic domains–their "core knowledge" of disciplinary concepts (Spelke & Kinzler, 2007)–as well as an understanding of the prior knowledge students are expected to acquire in earlier grades (Shing & Brod, 2016). Educational neuroscience experiments have used functional magnetic resonance imaging to evaluate the fate of intuitive notions following instruction. Misconceptions are not overwritten or erased from the brain with new knowledge acquisition, but rather are inhibited or suppressed by new synapses and circuits expressing a more sophisticated understanding (Masson, Potvin, Riopel, & Foerch, 2014). This provides a neuroscience-grounded explanation for a common observation in science classrooms: the difficulty of discarding naive beliefs and misconceptions.

KoS also includes understanding cultural differences and ethnic and language backgrounds (Allen et al., 2017). At first glance, these important student characteristics may appear beyond the scope of neuroscience. However, these lived experiences have been incorporated into the circuits of students' brains and constitute a form of prior knowledge (Han & Ma, 2014; Olsson, Knapska, & Lindström, 2020). Thus, on the contrary, viewing students' brains as primed for learning and personalized through experience provides teachers with a new lens for approaching students from different cultural, ethnic, and language backgrounds equitably.

Finally, KoS recognizes learners' different attitudes, motivational levels, confidence, and abilities to use different cognitive and metacognitive strategies (Goldman, 2009). Neurophysiologically, low amounts of stress hormones produce motivation whereas high levels prevent learning by inhibiting *synaptic plasticity*, the change that occurs in the connections between neurons during learning (Whiting, Wass, Green, & Thomas, 2021). Pedagogically, this translates into designing appropriate activities to challenge but not overwhelm students. Metacognitive reflection utilizes the same circuits involved in recalling and recognizing disciplinary content. Thus, metacognition contributes to mastery by reopening plasticity in these synapses for the refinement of memories (Kelley, McNeely, Serra, & Davis, 2021). KoS includes recognizing test anxiety, ADHD, dyslexia, limits on mental abilities, and giftedness (Voss et al., 2011). For such individual and group differences, neurophysiological measurements may be used to evaluate proposed interventions, as in dyslexia (Temple et al., 2003). Thus, neuroscience is already contributing mechanistic insights for many aspects of KoS.

TEACHERS CRAVE KNOWLEDGE OF STUDENTS

Cognitive and social science views of teacher knowledge dominate philosophies of preservice education (Appendix, Table 1). Yet, in-service teachers seek neuroscience knowledge, consider it important, and intuit that it will provide them with insights into how their students think and how best to teach them (Pickering & Howard-Jones, 2007). Teachers are in the business of structuring learning experiences for students, and are therefore curious about the process of learning and how the developing brain grows in its ability to process information, expecting that knowledge of these processes will help them support students in achieving learning goals (Hardiman, Rinne, Gregory, & Yarmolinskaya, 2012). In short, many teachers desire a more physiological KoS (Pickering & Howard-Jones, 2007). Descriptions of educational behaviors in psychological terms are useful because they relate to their lived experiences in the classroom. However, deeper, mechanistic explanations allow teachers to also consider the neuroscience of learning in their pedagogical choices. As a teacher remarked (Dubinsky et al., 2013).

> "Really, one [of] the things that's lacking in educational training for teachers is … the brain connections, the neuroscience connections by how people learn. You know, when we go through training, through the educational programs, it really focuses on learning theories from either an educational psychology perspective or a learning sciences perspective, there are no courses on how the brain develops, learns, and processes information."

This demand for neuroscience materials has been met by commercial publishers. However, commercial publishers have a predilection to promote neuromyths, or popular untruths about the brain (Howard-Jones, 2014). To counter this tendency, some master's level programs in educational neuroscience and translational centers have emerged, with initial reports of their outcomes or efficacy appearing (Friedman et al., 2019). Still, the question of how to alter teacher preparation to provide a neuroscience-grounded KoS to teachers looms large.

HOW TEACHERS APPLY NEUROSCIENCE KNOWLEDGE OF STUDENTS

An early argument against directly providing teachers with knowledge of neuroscience was that this content is too difficult or technical for teachers to comprehend–that many lack the "necessary" STEM background (Cruickshank, 1981). This led to a call for a special class of "neuroeducators" to translate the language of science into teacher-friendly talk (Cruickshank, 1981). However, this argument has been undercut by the success of the programs reviewed below. Studies of these programs demonstrate that teachers can directly comprehend neuroscience knowledge and apply it to their practices.

Neuroscience education for in-service teachers through PD provides insights into how teachers utilize neuroscience KoS (Dubinsky et al., 2019). One intensive neuroscience PD experience that has been implemented with teachers across the K-12 spectrum focused on synaptic plasticity as the biological basis for learning and memory; how this is modulated by emotions, stress, sleep, and drugs; biological brain development; and decision-making (Dubinsky et al., 2019). The program also modeled the best pedagogical practices and inquiry experiences according to the science education literature. Activities and materials appropriate for K-12 classrooms were used to facilitate teachers' learning of basic neuroscience in a manner in which they can identify with their students' learning processes. By combining these activities with discussions of how the neuroscience concepts could influence their professional practices, teachers had the opportunity to *make their own connections* between class practice and neuroscience. Rather than ask teachers to read primary neuroscience research literature, the PD focused on established, neuroscience, providing the opportunity for teachers to explore applications of these principles to their practices (Dubinsky et al., 2013). More generally, a number of studies have shown that teachers appreciate straightforward mechanistic explanations and enjoy constructing their own neuroscience knowledge and discussing connections to practice (MacNabb et al., 2006; Tham, Walker, Tan, Low, & Annabel Chen, 2019).

In-service teachers come away from such PD with a changed view of student learning and learning potential, capable of applying neuroscience knowledge as a filter in their pedagogical decision-making (Chang et al., 2021; MacNabb et al., 2006). Specifically, changes in teachers' views of students were as follows. Understanding synaptic plasticity and brain growth during childhood and adolescence shapes how teachers view students' ability to expand their cognitive abilities and social and emotional skills (Brick et al., 2021a; Schwartz et al., 2019). Synaptic plasticity provides a justification for extending opportunities to students to reach their potentials. Embracing this idea, teachers discarded the idea of students instantly absorbing everything that was said, replacing it with a view of students who learn variably from many diverse experiences that should be provided by the teachers (Chang et al., 2021). Teachers have expressed that to learn, students must interact over multiple encounters with content, a process that takes time, requires a safe space, and develops critical thinking skills (Schwartz et al., 2019). Teachers appreciated that physiological issues around emotions and stress can alter learning potential and that they, therefore, need to anticipate student needs (Brick et al., 2021a, 2021b; Chang et al., 2021).

The neuroscience-informed views of students led teachers to reason differently about their pedagogical choices and provide rich learning experiences. Teachers knew about student-centered pedagogies prior to the neuroscience PD; afterward, teachers understood why such pedagogies might be preferable (Chang et al., 2021; Schwartz et al., 2019). They improved the learning environments of their classrooms through increased emphasis on higher-order thinking, building deeper knowledge, engaging in more substantive conversations, and making more connections to real-world problems (Brick et al., 2021a; Roehrig et al., 2012; Tan, Amiel, & Yaro, 2019). When asked to revise a lesson plan of their choice at the end of one PD, participants ranging from pre-K to high school teachers incorporated more student-centered activities into those plans and justified those changes with neuroscience concepts (Schwartz et al., 2019). A year later, observations accompanied by interviews revealed that the same non-science teachers applied neuroscience concepts to thinking about how best to address students' needs in planned and enacted pedagogy and to guide in-the-moment pedagogical choices regarding content delivery and classroom management (Chang et al., 2021). These outcomes illustrate how neuroscience, as KoS, can profoundly impact teachers' pedagogical thinking, inform their choices, and support the enactment of reform practices (Walker, Hale, Annabel Chen, & Poon, 2019).

Neuroscience PD has also been successfully implemented in a tiered manner, with initial participants (Tier I) running workshops for additional teachers (Tier II) (Brick et al., 2021a, 2021b). Teachers in both tiers reported increased self-efficacy, motivation, and self-responsibility, measures considered as important components of teacher competency (Brick et al., 2021a). In follow-up interviews months after the PD, Tier II teachers emphasized that their new neuroscience understanding led them to focus on building relationships with students, providing students with social and emotional support, promoting self-regulation by replacing harsh disciplinary procedures with positive reinforcements, and utilizing more student-centered pedagogies. Note that this tiered program also covered the neural correlates of mental health issues. Participants reported being able to better recognize and help students with social, emotional, and behavioral problems (Brick et al., 2021b). These outcomes are evidence that embedding the learning principles of neuroscience can help teachers achieve a deeper understanding of the psychological aspects of KoS (Appendix, Table 1).

Other neuroscience-infused PD programs have achieved similar successes. In British Columbia, teacher-led integration of neuroscience ideas into pedagogical practices was accomplished through intensive lesson-study (Tan & Amiel, 2019). Teachers shifted how they understood knowledge construction and its relationship to teaching and learning, and were able to employ pedagogy consistent with the neuroscience of learning and memory. In a study in Israel, in-service teachers in a two-semester, elective neuroscience class within a master's level education program wrote reports on how they applied course content to their practices (Friedman et al., 2019). Qualitative analysis of the reports revealed teachers used neuroscience to justify choices among known pedagogies and to evaluate novel pedagogies. Moreover, teachers expressed that understanding how students' brains worked guided and changed their approaches to their students individually and collectively. Even a very short 90 min neuroscience introduction may alter how teachers perceive their own practices (Howard-Jones, Jay, & Galeano, 2020). Together these reports demonstrate how basic neuroscience educational opportunities positively influence teachers' thinking and pedagogical choices.

NEUROSCIENCE AS PART OF TEACHER KNOWLEDGE OF STUDENTS

The success of the neuroscience-infused PD programs reviewed above meets the pragmatic requirement, inspired by William James, that neuroscience must provide *useful* knowledge for educators, and thus deserves a place in teacher education programs and professional development. This raises the question: What aspects of neuroscience should educators know?

Since the brain forms the basis for the mind, to develop minds, teachers should understand the basic biological processes of the brain relevant to learning. Once teachers understand how learning occurs in students' brains, applying this information appears beneficial to planning classroom practices (Brault Foisy, Matejko, Ansari, & Masson, 2020; Chang et al., 2021; Tan & Amiel, 2019). Appreciating that synaptic strengthening requires both multiple activations and emotional salience, teachers revised lesson plans to provide engaging, meaningful opportunities for practicing material to be learned, and for applying this information (Roehrig et al., 2012; Schwartz et al., 2019). After learning that memories are stored in overlapping patterns of active synapses, teachers were observed to link new content to prior knowledge (Roehrig et al., 2012). Upon comprehending how a small amount of stress can motivate but high stress can inhibit learning, teachers reported increased use of student-centered practices and decreased harsh disciplinary practices (Brick et al., 2021a, 2021b). Learning about the development of synapses, circuits, brain myelination and the formation of new neurons provides a framework for guiding instruction with age-appropriate intellectual and emotional expectations (Darling-Hammond, Flook, Cook-Harvey, Barron, & Osher, 2020; García Carrasco, Hernández Serrano, & Martín García, 2015). In learning how brain circuits are rewired during learning to read, teachers come to see themselves as "cognitive enhancers" (Brault Foisy et al., 2020). And for children who struggle, experimental neuroscience is shedding new light on the cognitive challenges that children with dyslexia, dyscalculia, and dysgraphia face, and this is leading to the development of evidence-based programs and software to remediate their difficulties (Butterworth, Varma, & Laurillard, 2011; Drotár & Dobeš, 2020; Hoeft et al., 2011). Each of these ideas contributes to teachers' physiological KoS. Teachers must use these ideas to select appropriate PK and PCK to guide instructional choices to engage and motivate their students. How teachers grow into the challenge of applying this KoS to their pedagogical choices may require guidance (Katzir & Pare-Blagoev, 2006), as discussion and reflection during PD contributed to the results summarized above.

More programmatically, educational institutions are beginning to develop comprehensive inventories of the neuroscience principles and ideas that teachers should know. For example, a group of Deans from Schools of Education recently delineated six key questions to guide teacher education with associated neurocognitive principles (Deans for Impact, 2015). These ranged from knowing more about working memory and motivation to dispelling neuromyths. Some schools and groups of teachers have implemented pedagogical practices based upon neuroplasticity and correcting neuromyths (Kelleher & Whitman, 2018). A problem with some of these *ad hoc* educational efforts is that they emphasize pedagogical implications while minimizing the basic neuroscience underpinnings, potentially resulting in shallowly understood prescriptive practices. When these implications are abstracted too far from basic neuroscience principles (Howard-Jones et al., 2016), teachers may view them as equivalent to those from traditional psychological learning theories, missing the nuance and foundational explanations they bring. In contrast, in PD where teachers are given the opportunity to discuss what the physiological neuroscience concepts might mean for their own classrooms, strong connections between neuroscience principles and effective pedagogical practices have been documented (Brick et al., 2021a, 2021b; Chang et al., 2021; Dubinsky et al., 2013; Tan & Amiel, 2019).

NEUROSCIENCE, AS KOS, INFORMS THEORIES AND PEDAGOGICAL KNOWLEDGE

Neuroscience knowledge also provides a basis for evaluating learning theories according to what is biologically plausible (Goswami, 2019). The predominant theories of cognitive development from Piaget and Vygotsky have been joined by additional theories derived from cognitive neuroscience (i.e., neuroconstructivism, connectionism, statistical learning, reinforcement learning) (Goswami, 2019). The newer theories can increasingly explain many specific aspects of cognitive development and human learning (Goswami, 2019). Providing pre-service teachers with supporting neuroscientific evidence makes the theories more concrete, credible, and memorable.

Shulman's model carefully separated KoS from PK so that the former could be used to inform the latter. Respecting this distinction, neuroscience belongs in KoS, not PK. This separation heads off the mistaken expectation that neuroscience leads directly to specific pedagogies. Rather, knowledge of neuroscience guides teachers in choosing appropriate pedagogies (García Carrasco et al., 2015; Walker et al., 2019). Synaptic plasticity is important prior knowledge for ensuring that teachers continue giving students the opportunity to voice their preconceptions and misconceptions, to work through the arduous process of learning, and to self-correct with appropriate teacher feedback (García Carrasco et al., 2015). As another example, student agency is common to all active learning theories. Exercising agency in the act of choosing generates an additional striatal anticipatory neural signal not present during passively following directions that further strengthens hippocampal memory encoding and declarative learning (Murty, DuBrow, & Davachi, 2015). Meaning-making within personal narratives enlists the teller's agency, possibly providing predictive power for the development of brain networks for cognitive capacity in teens (Immordino-Yang & Knecht, 2020). Understanding how synaptic plasticity is modulated by agency can help guide teachers' choices of active learning pedagogies. As a final example, social, emotional, and affective physiological states provide the context for and strongly influence learning and educational theories (Immordino-Yang, 2011). Such neural processing provides value or salience signals that modulate learning and memory.

A major misconception regarding neuroscience's contribution to education is the belief that neuroscience can provide better teaching strategies than currently exist. This is likely not the case. What neuroscience has been able to contribute is to explain *why* some teaching strategies may be preferable (Brault Foisy et al., 2020). Neuroimaging methods have been applied to evaluate the effectiveness of pedagogical strategies such as spaced versus massed practice (Brault Foisy et al., 2020; Smolen, Zhang, & Byrne, 2016). In naturalistic classroom settings, correlations between brain activity in regions of the teacher's and learners' brains predict learning, and help distinguish between more and less effective pedagogies (Dikker et al., 2017; Pan et al., 2020). Adaptive scaffolding around a learner's prior knowledge produces more brain synchrony than non-adaptive instruction (Pan et al., 2020). To date, these neural measurements have only corroborated the efficacy of pedagogies already known to be preferable.

CONCLUSION

From the teachers' point of view, the academic distinctions between cognitive science, developmental science, educational psychology, and neuroscience–plus related and subfields–are confusing and possibly irrelevant. A teacher may not remember to look to educational psychology for an understanding of student motivation and anxiety, to cognitive psychology for theories of learning applicable to academic content, to developmental science for the trajectories and milestones of expansion of reasoning abilities, to developmental neuroscience for circuit-level explanations of dyslexia, and to neuroscience for information about synaptic plasticity. Regardless of their disciplinary origins, all of these concepts are relevant, to varying degrees and at varying levels of abstraction, to teacher preparation programs. All contribute to teacher professionalism.

In the reworkings of teacher knowledge since Shulman (Appendix, Table 1), the emphasis has shifted toward general and discipline-specific PK or cultural knowledge, and has de-emphasized the physiological KoS that teachers increasingly crave. Against this trend, it is important to remember the pragmatic criterion. To paraphrase the mathematician Hardy (1940), there is no permanent place in teacher education for useless information, regardless of its scientific validity. In this regard, neuroscience is on safe empirical ground. It provides foundational concepts that explain the biological underpinnings of the psychological behaviors relevant to education (Diamond & Amso, 2008), and provides evidence to support learning theories (Hendry & King, 1994). Studies of the efficacy of neuroscience-based PD programs provide important evidence that teachers can utilize neuroscience knowledge to make pedagogical choices. For these reasons, KoS should be positioned as a central focus of teacher education, with neuroscience as an integral part of its core.

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Conflict of interest

The authors do not have any conflict of interest to declare.

Ethical statement

This manuscript is a Commentary and does not represent original research. Therefore, IRB or IACUC protocols do not apply to this manuscript. To the best of our knowledge, all references cited within this manuscript complied with their institutional ethics panels' requirements.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Appendix S1. Supporting information.

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