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Radical neuroconstructivism: a framework to combine the *how* and *what* of teaching and learning?

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Recent advances in pedagogical research have called attention to the dynamic nature of the teaching and learning process in which the actors mutually influence one another. The understanding of how this works in the brain—the specialized neural networks related to this process—is often limited to neuroscientists but are slowly becoming available to other learning scientists, including teachers. A transdisciplinary approach combining the best information about observable teaching-learning processes from education with newer information from the neurosciences may aid in resolving fundamental questions in the learning process. Teachers' professional formation and development is often structured in segmented topical ways (e.g., pedagogy, evaluation, planning, classroom management, social–emotional learning), to identify important content knowledge (e.g., art, reading, mathematics, STEM), or to appreciate life skills (e.g., collaboration, critical thinking, social–emotional learning). While important, knowledge about the brain, the organ responsible for learning, is typically absent from teacher education. This paper reexamines the evidence from neuroconstructivism and the hierarchy of learning trajectories and combines it with evidence from psychology and the ways humans interact during the teaching-learning process to suggest *radical neuroconstructivism* as a framework within which to organize teachers' professional development. The radical neuroconstructivism framework may contribute to making the content knowledge of teachers' continual professional development more visible.

KEYWORDS

radical neuroconstructivism, mind-brain-education, core notions, learning sciences, learning trajectory, teacher education, holonic thinking, teacher professional development (TPD)

1. Introduction

The quality of education hinges on the quality of teachers (Barber and Mourshed, 2007; Engelbrecht and Ankiewicz, 2016; Boeren, 2019; Organisation for Economic Cooperation and Development, 2020). Teachers' continual professional development (TCPD) covers a wide range of topics (e.g., pedagogy, evaluation, planning, classroom management, social–emotional learning), subject areas (e.g., art, reading, mathematics, STEM), life skills appreciation (e.g., collaboration, critical thinking, social–emotional learning), and should exists throughout one's professional career (Sancar et al., 2021). There are few if any opportunities, however, for teachers to learn how these topics, subject areas, and life skills are supported by neural networks in the brain (Dubinsky et al., 2022), and fewer still about how to improve them (Peters et al., 2020). Understanding the neural underpinnings of knowledge building in the brain—or *neuro*constructivism—may create useable knowledge for teachers.

Placing TCPD within the "messiness" of classrooms (Tokuhama-Espinosa, 2014) and the relevance of cultural contexts (Hammond, 2014) may also contribute to improved learning outcomes as it acknowledges the ways one's learning is influenced by other actors. This dynamic exchange between students-to-students and students-to-teachers and vice versa influences what a learner takes from teaching and, consequently, changes what is learned (Bevilacqua et al., 2019). Recent research shows how individuals co-construct learning experiences (Vieluf and Klieme, 2023), which elevates the role of "others" in individual learning to the extent of deserving the label "radical" (Von Glasersfeld, 1995, 2013). Radical constructivism suggests that an individual's ability to learn is changed by context. To unite neuroconstructivism with the dynamic exchange of learning between actors, we propose a new theory of radical neurocontructivism.

The transdisciplinary field of Mind, Brain, and Education is uniquely positioned to support research into the theory of radical neuroconstructivism as it encompasses micro-level research at the level of neurons, to consideration of individual genetic and epigenetics traits, to the individual in within classroom dynamics, and all the way to macro-level research that consider social and cultural influences on learning (see Figure 1).

Despite the growth of the International Mind, Brain, and Education Society founded in 2007, and the Neuroscience and Education Special Interest Group of the European Association for Research on Learning and Instruction founded in 2010, advancements in designing a curriculum for teachers' professional development around concepts from neuroscience have been few and far between. To explore the potential contributions of radical neuroconstructivism theory to benefit teacher education, the first part of this paper defines and uses *holonic* thinking, a Greek word meaning something that is once a part and a whole. Holonic thinking is a newer conceptual framework to explain the relationships between the many elements in the educational process. This is followed by a brief historical overview of teachers' professional development between the 1980s and today, which shows radical neuroconstructivism as a natural outgrowth of past advances. The second part of the paper offers an example of early childhood education in math and language using studies from neuroscience that are the puzzle pieces of learning trajectories in these two domains. The paper concludes by summarizing how the *how* (pedagogy), *what* (curriculum), and *why* (Mind, Brain, and Education science) of radical neuroconstructivism may improve teacher education (Figure 2).

2. Part 1: Holons

In one of the most famous philosophical psychological undertakings, Arthur Koestler's *The Ghost in the Machine* (Koestler, 1967) observes that all things are both parts and wholes, which he labeled *holons*. "A holon, as Koestler devised the term, is an identifiable part of a system that has a unique identity yet is made up of sub-ordinate parts and in turn is part of a larger whole" (Edwards, 2003, para. 19). Later, Ken Wilber used holons to explain his All Quadrants, All Levels framework (AQAL), which showed the hierarchical nature of each part and whole (Wilber, 2001). This

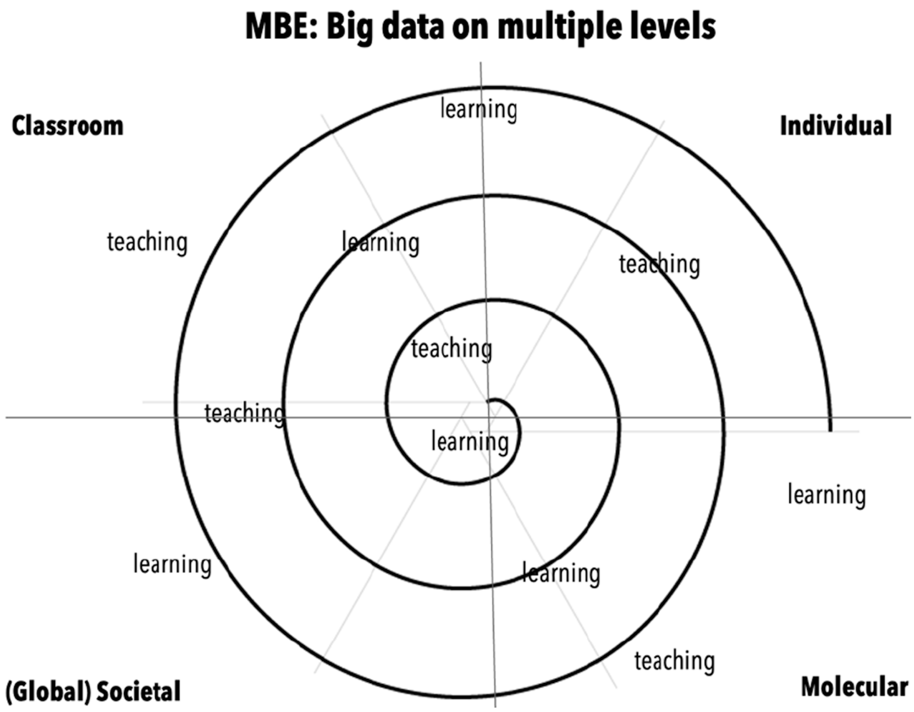

FIGURE 1
Mind, brain, and education research on multiple data collection levels (Tokuhama-Espinosa, 2017).

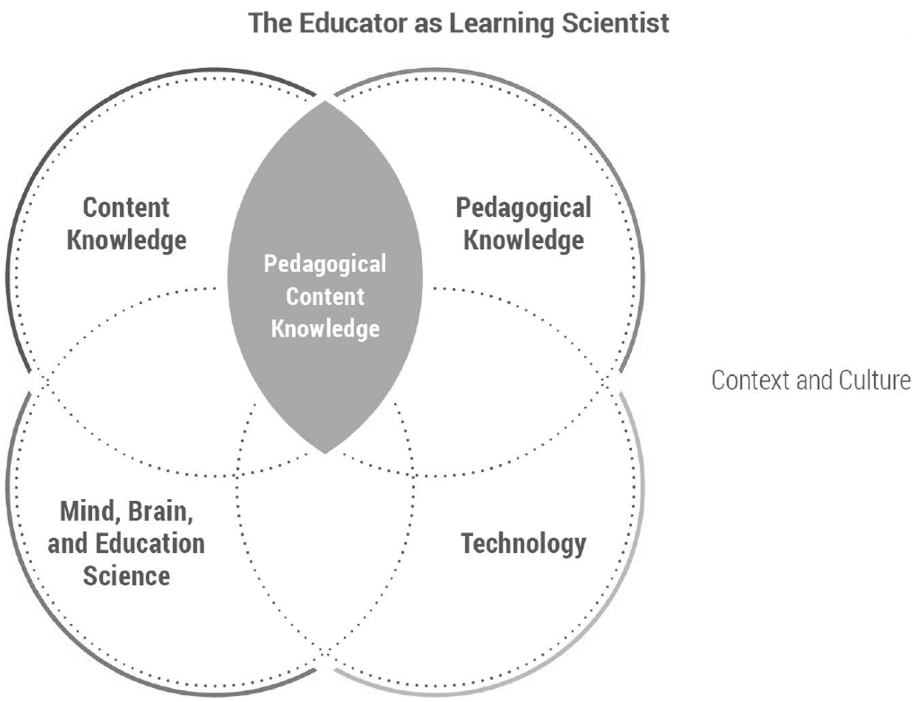

FIGURE 2
The educator as a learning scientist (Tokuhama-Espinosa, 2021a,b). Used with permission of the author.

allowed Gallifa (2019, p. 15) to describe "integral thinking" using a holonic approach to explain the complex nature of all learning through relationships build on hierarchies.

Based on Koestler's definition, everything in the natural world is a holon. A child, for example, is a holon as he is a whole on his own, but he is also a part of a family. A leaf is a holon because it is a whole unto itself, but it can also be a part of a tree. A person's brain is a holon as it is a whole entity on its own, but also part of the person's body. Holonic thinking embraces the idea that not only can everything be a part of something bigger, but each holon can be broken down into smaller parts as well. The child is made up of body parts, which in turn are made of flesh, blood, bones, and muscles (that can themselves also be broken down into ever smaller parts). The leaf can also be broken down into fibers and chemicals, which in turn can also be broken down further. A person's brain can also be broken down into different types of cells, proteins, and so on. In short, everything is a holon, a whole on its own and a part of bigger things that can also be broken down into smaller elements.

2.1. Holonic thinking and teachers professional development

Holonic thinking offers a new lens through which to view challenges in teaching and learning. Education is a holon. It can be considered a part of the Learning Sciences, as well as an academic field on its own, and can be broken down into smaller elements. Teacher education is also a holon. It is part of Education, but can also be broken down into elements, such as *how* to teach [pedagogy and didactics (methodology, activities and strategies)] and *what* to teach (content, curriculum, learning how to learn). The ability to evaluate and give good feedback; how to use technology appropriately; what is needed to create inclusive classrooms; how to differentiate; the cultivation of social–emotional skills to nurture oneself and others, among other elements, are all holons and sub-elements of teachers' continual education. Both pedagogy and curriculum are parts and wholes, as are all of the other topics and skills that contribute to good teaching and successful learning.

Merging the *how* (e.g., pedagogy) with the *what* (e.g., curriculum) of the teaching-learning dynamic yields teachers' pedagogical content knowledge (TPCK) (Gess-Newsome, 2013). In contrast to general best practice teaching, TPCK displays a more nuanced understanding of the interventions that are most appropriate given a specific subject matter and age group. For example, the specialized knowledge teachers must have to anticipate the errors and knowledge of how to correct them differs when teaching math to 3rd graders versus teaching English to high school students. Shulman's (1987) seminal work in this field elevated the mechanistic approach of teaching from a simple delivery system of facts to include a more subtle and precise knowledge base required of teachers both of their subject matter and for the correct pedagogical interventions that can be used to reach educational objectives.

Technology was added to TPCK around 2004 and yielded what many now call the TPACK (Technology, Pedagogy, and Content Knowledge) Model (Mishra and Koehler, 2006). Technology, and specifically educational technology tools, both aid traditional learning as in the correction of objective assessments (e.g., multiple-choice question quizzes), for instance, as well as force society to rethink the role of traditional educational design. *If the only goal of schooling is to gain knowledge and knowledge can be learned using mobile devices, then why go to school at all?,* one might ask. Such reflections help elevate the expectations of schooling and also change the expectations of what teachers' roles are within those schools. For example, the existence of technology that provides content knowledge in a subject area like math reduces the expectation that teachers use time in class reciting math facts (knowledge) (Donahoe et al., 2019) and elevates expectations that they now use their time applying the use of that information (skills), or how to cultivate values around the information, such as learning how to think like a mathematician (attitudes) (Seufert et al., 2021). Some argue that the role of school was never about transmitting factual knowledge, but rather to nurturing of the whole child (Perkins, 2009) by considering his context, likes and dislikes, and particular learning needs (Moon et al., 2020), and that technology can give teachers more time to personalize the teaching-learning experience (Schmid et al., 2022).

Technology has also introduced Artificial Intelligence and machine learning into educational processes (e.g., ChatGPT) which has forced teachers to pivot in ways that will likely change the teaching-learning dynamic forever. Whereas in the past students were judged by their ability to produce *answers* on standardized tests (Cunningham, 2018), large language models like ChatGPT will force students to come up with better *questions* relevant to their unique contexts (Lund et al., 2023). Technology can serve to make some types of learning more personalized and tailored to individual needs, enhancing learning outcomes. To learn to leverage these new technologies and to participate in their design, teachers will necessarily also need to learn more about the ways that both artificial intelligence and real human intelligence work. This new need has catalyzed a renewed interest in the learning sciences, specifically Mind, Brain, and Education (MBE) science.

In viewing the teacher as a learning scientist one can combine pedagogy, content, technology and MBE to suggest a new approach to teacher formation (Tokuhama-Espinosa, 2021a,b). Mind, Brain, and Education science adds a *why* to the *how* and *what* of teaching as it explains the reasoning behind certain teaching interventions (pedagogy: *how*) and content (curriculum: *what*).

As the newest addition to teachers' basic skills, Mind, Brain, and Education science and the International Mind, Brain, and Education Society (IMBES) were founded in 2007 to help practitioners understand how the brain learns in order to verify the best teaching methods to reach the most students (Tokuhama-Espinosa, 2010). MBE has proven implications for pedagogical interventions (Tokuhama-Espinosa, 2014, 2021a,b; Wilson and Conyers, 2020) as well as has made inroads in curriculum (Larrison, 2013). According to Dubinsky et al. (2022, p. 267), "the foundational contributions from neuroscience regarding how learning occurs in the brain reside within one of Shulman's seven components of teacher knowledge (Shulman, 1987, p. 8), Knowledge of Students… teachers must also (and increasingly) know what happens inside students' brains." It has been suggested that "knowledge of learners and their characteristics" (Shulman, 1987, p. 8) should now include clarity about how the brain understands concepts in domain-specific areas (e.g., Hawes and Ansari, 2020), leverages emotions for better cognition (e.g., Li et al., 2020), and co-constructs meaning making in group situations (Immordino-Yang et al., 2019).

Holonic thinking can be used to reframe the way we view teacher education and our understanding about the teaching and learning process. Both philosophers (e.g., Procter, 2011) and neuroscientists (e.g., Lamme, 2006) believe learning is based on fundamental building blocks of knowledge, which permit the construction of increasingly complex thinking (Hernández Armenta et al., 2019). Thinking is a holon that is part of the learning process itself, and it can be broken down into smaller and smaller parts. Disaggregating this thinking process into its smaller parts allows for a more precise understanding of all of the elements that contribute to how people learn both in classroom settings and in the world more broadly. To construct new learning, people build on previous knowledge using the foundation of what have been called core notions (Bada, 2015). Some of the building blocks of learning are explained in neuroscientific studies, but few teachers benefit from this information in their initial teacher training or in continual professional development (Deans for Impact, 2015). Furthermore, the majority of the contributions from neuroscience to education are related to pedagogy, not curriculum. In a review of all the articles from the *Mind, Brain, and Education* journal 2007–2018, just 24 of 312, less than 1%, related to curriculum (Nouri et al., 2022, pp. 58–59). This confirms Dubinsky and colleagues' belief that "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" (Dubinsky et al., 2022, p. 267).

One potential way to extend MBE into Education both pedagogically and through curriculum is through *radical neuroconstructivism*. Radical neuroconstructivism is an as-of-yet untested theoretical framework for understanding the teaching-learning dynamic. It is difficult to prove as it rests against the backdrop of a student's prior experiences and contexts which vary greatly. It also depends, however, on universal building blocks, meaning some generalizations relating to all humans can be posited.

3. Radical neuroconstructivism

Constructivism has been used successfully as a framework to explain the way the mind orders the hierarchy of learning concepts, beginning with an approach from developmental psychology and spilling into education (Piaget, 1923). To construct new learning, people build on previous knowledge using the foundation of these core notions (Solis-Stovall, 2020). The individual does not live in the world alone, however, so many researchers, especially those in social learning theory (e.g., Bandura, 1977), raise the importance of constructivism within environments and social contexts. When the environment and the role of others is also incorporated into the constructivist learning model, this is called *radical constructivism* (Von Glasersfeld, 1995, 2013). Ernst Von Glaserfeld used the constructivist ideas suggested by Vico (1710), Ceccato (1964/1966), and Piaget (1968) to which he added on the cyclical, iterative processes that occurs as people try "to order the as such amorphous flow of experience by establishing repeatable experiences and relatively reliable relations between them," (Von Glasersfeld, 1984, p. 5). Von Glaserfeld's ideas were firmly grounded in strong philosophical roots but they carried over naturally into the teaching and learning environment as the means by which societies devise formal education. Von Glasersfeld (1984, p. 20) uses "radical" to emphasize the relationship of a person to reality and explains that rather than a "picture-like (iconic) correspondence or match, radical constructivism sees it as an adaptation in the functional sense." This means that the very contact with others or with new information would change a person's understanding of it. An idea in one's head about how to approach a problem, a work of art, or a piece of literature, is changed by the simple act of articulating it out loud for another person. While words facilitate thinking, they are not the same thing as thinking. One's understanding of one's own ideas require no explanation to one's self; once put "out in the world" one must modify the choice of words to meet others' levels of understanding. Furthermore, teachers must modify this language use to meet a variety of learners' needs in the same setting. This means that what is thought cannot always be articulated clearly to others, resulting in the voice in our heads being different than the one we hear as we speak (LaValley, 2022).

A second aspect of the "radical" nature of thinking and learning relates to the individual themselves in time. As all new learning passes through the filter of prior experience (Tokuhama-Espinosa, 2008), and the older we get the more experiences we have, our interpretation of the world becomes more colored by what we already know. For example, reading *The Diary of Anne Frank* at age 13 is different at age 18 or 30 or 50, not because the book is different, but *you* and your context are different.

Radical constructivism emphasizes the role that others can play in influencing how an individual thinks about information. A person may have one kind of idea in their mind, but when they articulate this in words to another person, the idea changes Hitchcock, (2018). And by listening to the response of the other to the idea, the idea is again changed. This dynamic process of idea transformation is what turns constructivism within the individual into a social exchange in the world (De Soto, 2022). Teachers know that classroom exchanges between students and with themselves modify the way they think about information.

After radical constructivism, a newer concept from neuroscience, *neuroconstructivism*, took hold. *Neuroconstructivism*, like its predecessor *constructivism,* requires that lower or base level concepts be learned before more complex ideas can be built upon them and that this occurs in a neurophysiological way structuring primary networks before secondary ones can be scaffolded upon them. Dekker and Karmiloff-Smith (2011) were some of the first to suggest that the combination of behavioral studies, neuroimaging, and genetics research in both typical and atypical populations pointed to the existence of neuroconstructivism. By Karmiloff-Smith et al. (2018) were able to formulate a new theory of human development based on neuroconstructivism.

"Neuroconstructivism" is a term used to explain the physical scaffolding of core notions and conceptual knowledge (Broadbent and Mareschal, 2019) "that influence the emergence of mental representations in postnatal development," (Westermann et al., 2007, p. 75). The brain makes basic neural connections, then successively more complex ones based on experiences which are unique to the individual (Mareschal et al., 2007; Westermann et al., 2007, 2011; Karmiloff-Smith et al., 2018). As Westermann and colleagues pointed out in their seminal article *Neuroconstructivism* (Westermann et al., 2007, p. 75), "Cognitive development is explained as emerging from the experience-dependent development of neural structures supporting mental representations." The scaffolding of conceptual understanding permits the construction of neural networks that eventually become the learning manifested in observable behavior, such as the ability to read a story or to do a math problem. Earlier studies in neuroconstructivism showed that when certain fundamental networks were missing, a child was unable to perform certain tasks and future tasks that relied on that initial task. For example, a child can scaffold a new understanding of subtraction upon the basis of addition. If the child knows how to add well, then learning to subtract takes relatively few steps to master. However, many children have gaps in core notions in mathematics and because they have missing conceptual knowledge in addition, they are unable to easily learn subtraction. This is not only true for math but for every other subject taught in school or experienced in the real world.

In 2019, Tokuhama-Espinosa suggested that this promising new idea could be merged with Von Glaserfeld's thinking and coined the term *radical neuroconstructivism.* Building off both the dynamic, iterative exchange of an individual with his or her surroundings, and the constant co-construction of neural networks of the brain's design and on a natural hierarchy of conceptual knowledge, this paper suggests that radical neuroconstructivism can potentially create the framework to explain how people learn.

3.1. Meaning making

This paper suggests that the *radical* aspect of radical *neuro*constructivism involves "meaning making," made popular thanks to Neil Postman and Charles Weingartner's chapter in *Teaching as a Subversive Activity* (Postman and Weingartner, 1969). In their work they point out that "meaning making also forces us to focus on the individuality and the uniqueness of the meaning *maker*," (Postman and Weingartner, 1969, p. 91). This was a shift from prior teaching and learning models in which school subjects (math, language, art, history, and so on) were meant to be learned by all individuals in the same way without much consideration for the variability among students. Postman and Weingatner valued that the way people understand their world and make meaning depends to a great extent on what they already know and how they have already habituated responses to certain contexts and stimuli. When one begins with the meaning *makers* (students) in mind, and the many differences they each have, it becomes clear why the learning processes in school do not always go to plan; the individuality of the learner changes the outcomes.

To make meaning of one's world, an individual first perceives the environment through the senses, as Aristotle suggested 2,500 years ago (Caston, 2020). This sense perception is perceived and interpreted in the brain by comparing what is known from prior experiences to the incoming information from the outside world (Tokuhama-Espinosa, 2008). The prior experiences a person can have are grounded in both formal and informal learning, as well as based on life experience. Life experiences and a person's environment also includes one's culture, which like all social environments, influences learning (Gay, 2018). People then construct meaning by taking the new information that is being perceived in the brain and comparing it with what they already know from prior experiences including their cultures and contexts. Contexts and cultures include contact with other people in settings like schools and with teachers and students.

Complementary to Postman and Weingartner (1969) work is a newer interpretation of *meaning making* from Mary Helen Immordino-Yang's lab. She suggests knowing how others feel (empathy) and think (mentalizing), then comparing that to one's own thinking and feeling, helps derive meaning (Immordino-Yang and

Knecht, 2020). That is, seeing how others react in situations and comparing that to how one would act themselves in the same situation helps people make meaning out of the world: "Radical neuroconstructivism changes based on the student-teacher and student–student dynamics, and other human exchanges converging with what the student already knew about the information mediated by the pedagogical choices of the instructor," (Nouri et al., 2022, p. 115). The interaction with the outside world, compared with internal knowledge and memories, is modified by other students and by the teacher, making it "radical" as compared to static (Nouri et al., 2022). Radical neuroconstructivism explains why different students react differently to teaching strategies and activities. The unique reaction of each student to what the teacher and other students do in the classroom changes the way the student thinks about the information, and ultimately how he or she learns.

Students come to class with their past experiences, their cultures, and their genetic profiles which then interacts with exchanges they have with other students, with their teacher, and the teacher's choice of pedagogies. The intricate interaction between this large number of complex variables results in learning. As shared in *Crossing Mind, Brain, and Education Boundaries* we contend:

> Rather than a simple "Teach A-Learn A" scenario, MBE (Mind, Brain, and Education) teachers appreciate that learning is complex, and influenced by multiple factors. MBE practitioners understand that:
>
> (a) students come to class on an uneven playing field due to genetic inheritance;
> (b) students do not share the same prior experiences;
> (c) what the student already knows influences how they learn;
> (d) knowledge, skills, and attitudes influence learning;
> (e) the student's relationship with the other learners influences learning;
> (f) the student's relationship with the teacher influences learning;
> (g) the teacher's execution of the methodology, strategy, or activity influences learning;
> (h) the learner's self-perception in the class context/environment influences learning;
> (i) what else is vying for the student's attention can influence learning.
>
> These different actors, actions, reactions, and interactions can all influence learning outcomes (Nouri et al., 2022, pp. 115–116).

Taken as a whole, radical constructivism suggests that the individual's conceptual knowledge of the world is shaped by what he or she already knows, and how, when, why, and by and with whom the stimuli occurs.

4. Core notions as basic building blocks of cognition

The concept of core notions has been posited in philosophy (e.g., Schaffer et al., 2009), demonstrated in cognitive psychology (e.g., Tuominen and Kallio, 2020), and imaged in neuroscience (e.g., Skerry and Saxe, 2016). Core notions are pre-requisite knowledge at each stage of the learning process. Furthermore, each progressive level of knowledge has its own core notions and depends on those that proceed them (Sporns, 2022); counting has different core notions than calculus, for example, *and* calculus depends on counting. Similarly, higher order language depends on the lower notions that sustain them; the core notions within word choice are different from higher order language notions such as metaphorical thinking, for example. Metaphorical thinking, in turn, depends on word choice (Black, 1962). In the best-case scenario, the curriculum or order of subjects a child learns, should first introduce fundamental core notions and once mastered, advance to subsequently more complex notions.

Countries around the world use the evaluation of math and language as proxies for intelligence (Tokuhama-Espinosa, 2019) often in combination with more complex tools that depend on them, such as reasoning (Flanagan and McDonough, 2018). Both math and language are comprised of "core notions" or fundamental building blocks of knowledge, which permit the construction of learning and progressively more complex thinking (Hernández Armenta et al., 2019; Solis-Stovall, 2020). Examples of "core notions" include any fundamental or pre-requisite knowledge needed to complete a higher order task and are characterized by *thinking* states rather than *process* memorization. For example, zero ("0") is a complex notion, which, if misunderstood, can lead to problems with understanding "ones" and "tens" and eventually decimals, negative integers, and other key notions in mathematics (Hansen et al., 2020). In a second example, the core notion of a mental number line can be used to see addition or subtraction problems inside one's head (Dehaene, 2003; Haman and Lipowska, 2021). Problems like "$1+2=3$" are visualized in the mind's eye and such visualization is vital to developing efficient, accurate and speedy arithmetic skills (Sari and Olkun, 2020). An understanding of zero combined with a mental number line permits a visualization and understanding of negative numbers, and eventually the addition and subtraction of both positive and negative integers (Vest and Alibali, 2021). If zero or the mental number line are not learned by children, they will be unsuccessful in early math, and consequently higher math. Missing core notions in children are a primary reason kids "hate math" (Liu, 2016); the inability of teachers to identify these gaps is exacerbated by the fact that teachers themselves often have missing core notions (Ball, 2017). Missing core notions in teacher knowledge are also responsible for poor math and language learning by their students (Loch et al., 2015), signifying a systemic problem.

Unfortunately, many students advance through the education system with progressively complex missing core notions (Rist, 2017) for which teachers are unprepared. Bartelet et al. (2014, p. 657) noted that learning difficulties in math can spring from at least six different origins: "(a) a weak mental number line group, (b) weak ANS (Approximate Number System) group, (c) spatial difficulties group, (d) access deficit group, (e) no numerical cognitive deficit group and (f) a garden-variety group," suggesting that a more nuanced look at both gaps in mathematical instruction as well as diagnosis of mathematical sub-types of errors is necessary to help students achieve. If teachers do not know about core notions or their hierarchy in brains, they cannot easily identify the types of errors being committed by students. This is an example of what Dubinsky and colleagues meant by improving teacher Knowledge of Students "and what happens inside their brains," (Dubinsky et al., 2022, p. 267).

Research into language has also identified many core notions which can go unattended in early childhood education. One area that has received a lot of attention is vocabulary. Educational research has demonstrated for years that rich, age-appropriate vocabulary lays the foundation for complex thinking (Hirsh-Pasek and Golinkoff, 2003) and that poor vocabulary is correlated with academic failure (Baker, 1995). Hart and Risley (2003) "*The Early Catastrophe*," showed a "30 million word gap by the age of 3" for children from lower social economic status homes due to less exposure to rich conversational exchanges, fewer books in the home, and parental knowledge of language development (Johnson et al., 2017). Researchers warn that "denying the existence of the 30-million-word gap" suffered by underserved children "has serious consequences" (Golinkoff et al., 2019, p. 985). Therefore, explicit vocabulary instruction is a part of several early childhood training programs, but not all. Despite neuroscientific evidence showing that "children's conversational exposure is associated with language related brain function," (Romeo et al., 2018, p. 700) that do not exist without human conversation, other researchers have pointed out that "talk alone will not close the 30-million word gap" (Wasik and Hindman, 2015, p. 50) and that meaningful interactions with language use in varied contexts are necessary to fill in the gap. Appropriate word use in the right context with increasingly complex patterns is fundamental to language development but not all early childhood education programs emphasize this and not all teachers know vocabulary is a fundamental building block in learning.

Other core notions in language development relate to normal speech patterns, including the grammar and syntax that is acceptable in local cultural contexts. While all humans learn to speak from an innate language sense (Chomsky, 2000; Pinker, 2009), the parameters of acceptable speech differs by country (e.g., British to American), region (e.g., Hawaii to Texas), district (e.g., English in the Bronx versus English in upper Manhattan), and even neighborhood (e.g., East Los Angeles versus West). Furthermore, the way humans speak differs greatly from how they write, especially from informal to academic contexts (Chafe, 1985). This puts children whose core notions of grammar and syntax that differ from standard English in school at an academic disadvantage from the start (Au, 2009). When the school's standard English differs greatly from the home language, students first need to learn the "foreign" language of school before they can be successful in other subjects. This sets up many for failure. Many find learning the school language a burden and decide they are not "cut out for school," and/or "hate reading," (Hale and Crowe, 2001), and too many drop out (Rumberger and Lim, 2008) for this reason. This paper proposes that teaching core notions in language in a more orderly trajectory may change students' negative attitudes toward education as the neuroconstruction of core notions in an orderly way may ease the path by creating a more solid early learning foundation.

In this paper it is suggested that a deeper and better understanding of the radical neuroconstructivist building blocks of cognition may permit a more precise and orderly introduction of skills that would be coherent with the brain's natural progression from lower-to-higher-level knowledge. This would improve the design of the curriculum, allowing more children to succeed.

5. Teaching and learning: practical applications of radical neuroconstructivism

While psychology has contributed to educational best practice for over 100 years (Berliner and Calfee, 2014), contributions from neuroscience have only recently been regularly incorporated into teacher professional development (Deans for Impact, 2015). Thanks to neuroscientific insights, there have been improvements in pedagogy, didactics, strategies, activities, and methodologies for learning at all levels of education (K-16). This is especially true of new knowledge about the dynamic exchange between cognition and affect (e.g., Immordino-Yang, 2015), meaning making (e.g., Zittoun and Brinkmann, 2012) at the crossroads of culture and cognition (Rawlings and Childress, 2021), and the importance of student-teacher relationships (e.g., Hattie and Zierer, 2017).

While *how* to teach has benefitted greatly from neuroscientific insights, *what* to teach has received less attention; the promise of neuroscientific insights into shaping the design of curriculum, such as in early literacy or math learning, is an underexplored area for educators. A key impediment to the use of neuroscientific knowledge in education is that the puzzle as a whole has not been constructed using all of the parts that are available.

6. Part II: learning trajectories and radical neuroconstructivism

The second part of this paper uses the examples of early years language and math to explain the holonic thinking from Neuroscience, Psychology and Education that can lead to a better neuroconstructivist curriculum design for schools. Education and Psychology have helped construct a relatively orderly curriculum (Tokuhama-Espinosa, 2019), which takes into consideration human variability (e.g., Mezirow, 2018). It is possible that additional evidence from Neuroscience can bring a more nuanced understanding of typical gaps in notions that children may experience. We propose that the ability to diagnose missing core notions earlier will allow more timely and accurate interventions in early childhood education.

Learning depends on the quantity, quality, and timing of exposure to learning objectives (Paolini, 2015). The literature suggests the earlier an academic competency is introduced to a learner, and the stronger its subsequent constructivist development, the more likely a positive learning outcome in that competency (Bakken et al., 2017) due to the quantity and quality of exposure. The literature also suggests that quality experiences at pre-school benefits both kids who had enriching home experiences and those who did not (Fuson et al., 2015). Klein and Starkey's research showed that a broad socioeconomic gap in informational mathematical knowledge was present at the beginning of the *pre-kindergarten* year. This gap included not just numerical concepts and arithmetic reasoning, but also spatial concepts and geometric reasoning, knowledge of patterns, and nonstandard measurement (Klein and Starkey, 2004). One theory for this occurrence relates to the kinds of play experienced by different socio-economic groups (Missall et al., 2015). This means some kids arrive at school with missing core notions as compared with their peers due to the contexts in which they were raised. Quantity, quality, and timing are aided by exposure to core notions in a *logical order* which strengthens neural pathways for future learning (Karmiloff-Smith, 2009; Galván, 2010). Nowhere is this more evident than in research on early language development and early math.

The stimulation of language development (i.e., vocabulary, correct word order, social cues for interaction, and so on) begins in the home with the family and is generally developed further in regular school settings by trained educational professionals. Similarly, pre-numeracy skills (*ordinality* as parents count a child's fingers and toes out loud; *magnitude* as he is given "more" or "less" of an object; *symbolic numeric representation* as he blows out the candles on a birthday cake, and so on) aid in the development of a child's *number sense* (Dehaene, 2011) and are cultivated in a similar pattern (Campbell, 2014) through adult-child interaction. High-quality early childhood education can play an important role in the effective development of early academic skills development (Campbell et al., 2012) but requires a home (parent)-school (teacher) partnership with a shared plan (Missall et al., 2015). We suggest that by disaggregating math and language into sub-skills in a neuroconstructivist trajectory for mastery, we may potentially improve the diagnosis of problems and aid in the selection of more accurate remediating activities with the goal of ensuring all children have a successful start to school.

It is only since the turn of the century that neuroimaging studies have offered definitive proof of the changes in the brain during infant learning. This includes cognitive development such as typical growth rate, myelination, top-down modulation, and changes in cortical hubs, (Deoni et al., 2011; Fransson et al., 2011; Holland et al., 2014; Dempsey et al., 2015; Emberson et al., 2015). While teachers and parents generally understand that infants learn at an astounding rate, few are aware that infants have a preverbal early number sense that permits them to estimate quantities, gauge relative size and judge spatial orientation (Dehaene, 2011). One way to make these ideas clearer to parents and teachers is by showing neuroconstructivist studies alongside more familiar learning trajectories shared by pediatricians (Morris et al., 2020). To do this, it is important to update basic professional knowledge in the learning sciences for both math and language.

6.1. Four categories of networks found in the literature

Understanding the neural networks of learning requires holonic thinking in which the smallest of parts are placed in context with their larger wholes. Between 2013 and 2023 we reviewed over 1,000 studies on early math and literacy and sought to create a taxonomy of early learning using their content. Initially, research was limited to domain-specific studies that looked at language and mathematical networks in the brain in young children. Domain-specific networks overlap significantly between language and math (Caravolas et al., 2012), and include pathways for symbols, patterns, order, relationships, and categories (Tokuhama-Espinosa, 2019). It soon became apparent, however, that while learning to read or do math involves domain-specific areas, learning also depends heavily on the general cognitive abilities of memory, attention, and executive functions (specifically inhibitory control, cognitive flexibility, and working memory), and in fact, without well-functioning general cognition, it was all but impossible to have domain specific instruction.

In addition to domain-specific networks and general cognitive networks, the literature also identified numerous studies related to the context in which a person learns. A learner's relationships with others in the class and with the teacher influence learning (Frey et al., 2019), as does the student's self-esteem and belief in him or herself to learn (Agir, 2019). Motivation is also part and parcel of the learner context (Ahn et al., 2019), and one's awareness of the impact their social contexts, including culture, has an important influence on one's ability to learn in a given classroom setting (Osher et al., 2020). The literature clearly shows the uneven playing fields upon which different children begin their lives. The risk and protective factors of family (parents' education, SES, marital status), homes (homelessness, proximity to parks and libraries, daycare options), as well as the impact of culture and social contagion on well-being influence learning.

Finally, there were also several studies concerned with the physiological sensory networks related to the senses, specifically hearing, vision, and touch. Well-functioning sensory systems influence learning. While there were fewer studies about the role of gustatory and taste influence on learning, a student's ability to see, hear, and learn through touch or haptic knowledge (Connolly, 2019) was vital to every learning encounter. Vision and hearing tests are standard procedure in many early childhood education programs, but not in all (Oosthuizen et al., 2023). This suggests 16 neural networks divided into four categories explained below (Figure 3).

The four categories have a total of 16 distinct neural networks within them, and those networks sub-divide into numerous pathways, which we define as *core notions* in domain areas such as math (Table 1) and language (Table 2). For the purposes of this paper, the neural pathways are considered "distinct" if one or more brain areas is different. For example, auditory working memory and visual working memory differ in the sensory input but not in memory areas and are treated as distinct networks (Figure 3).

6.2. Domain specific networks

The concept of "learning trajectories" (Gorard, 2006) is based on research into "hierarchies of skills" (Kuhn et al., 2000) and the general concept of constructivism proposed in the mid-1900s in which basic concepts are established before higher-order thinking occurs (Piaget, 1967). We generally presume that the curriculum structure of a country, state, or district should order the information we consider valuable to teach into the right trajectory so that students can logically advance from one concept to another. Curriculum structures around the world are surprisingly similar in terms of subject area content. The same subjects are taught all around the world at roughly the same time (Tokuhama-Espinosa, 2019), which allows for international comparative studies like TIMMS (Trends in International Mathematics and Science Study) and PIRLS (Progress in International Reading Literacy Study). Independent of country values, social economic status, culture, public-private-parochial status, political inclination, age group, and rural–urban status, all school systems, large and small, teach math and language. Language and mathematics are cornerstones of all educational programs worldwide (Pinar, 2013), and are vital to both an individual's success as well as country competitiveness (Organisation for Economic Cooperation and Development, 2021). Among countries that conduct national exams, these are the only two universally tested subject areas due to the foundations they lay for other academic fields (Martin and Mullis, 2013), including history, art, the natural, social, computer, and hard sciences. Despite their importance, even within-country studies show there is no consensus on the best ways to teach core subjects such as math and language.

6.2.1. Neuroconstructivist mathematics

Constructivism can explain why some learning goals are not met. As mentioned earlier, a child cannot learn subtraction (*learning goal*) if he does not understand addition (*pre-requisite knowledge*). To

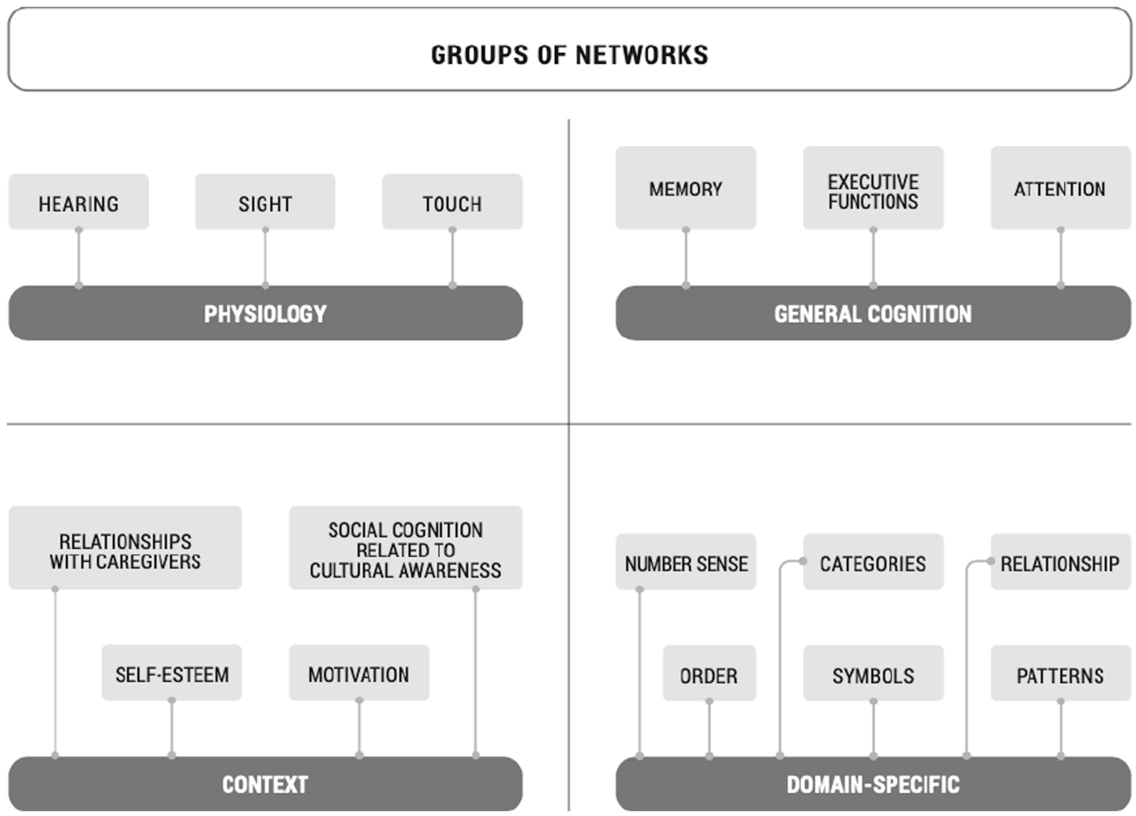

FIGURE 3
Four categories of networks found in the literature.

be successful in basic arithmetic, he will first need to understand everything underpinning the concept of addition, and then make his way to the higher-order skill of subtraction, which involves dozens of core notions. If any one of the pre-requisite skills laid out in the hierarchy is not developed properly, the child will not be unable to master the new knowledge upon which it is based (Vergnaud, 1982). It is important to acknowledge that some children will learn to mechanically identify the pattern of subtraction questions and appear to dominate that skill, but in reality, they will simply be using extended working memory and knowledge of patterns to feign knowledge (Ball, 2017). True understanding means the learner can comprehend, identify, explain, use, and *transfer knowledge* as evidenced by creating their own problems correctly (Ringel and Springer, 1980).

Math, like all subject area, has four categories of networks were sub-divided by 16 neural networks. In math, we have further divided the networks into smaller parts—core notions—or neural pathways. In our review of the literature on the neural correlates of math, we have identified over 130 distinct pathways (Table 1), which can be observed in over 180 behaviors related to mathematical development. For example, the observable, visible behavior of counting can be observed in a classroom as the student counts on his fingers, counts objects, sings a song about counting, labels number symbols on a number line, among dozens of other activities. The invisible neural pathways involved in counting include decoding, discrimination and enumeration; distance and congruity; finger counting; inhibitory control and visual processing; number versus non-number symbols, among others (Table 1). In both math and language there are more observable behaviors than invisible networks, suggesting that the same networks sub-serve more than one behavior.

The main ways neuroscience can contribute to educational practices is by (a) assuring all neural pathways are stimulated through a variety of activities so that (b) all sub-skills and prerequisite knowledge are learned. This can be done if (c) core notions are approached in an orderly, hierarchical way. Additional benefits include the ability to (d) identify missing core notions early, therefore (e) making teaching interventions more precise, which would prevent children from school failure.

Table 1 is not exhaustive, and offers just a sampling of possible core notions, some of which have additional sub-elements.

Other evidence shows how the brain learns to code mathematical symbols and to distinguish between "3," "three," and "***" in a *triple code* (Dehaene, 1992; Dehaene and Cohen, 1995; Dehaene et al., 2003; Schmithorst and Brown, 2004; Klein et al., 2014), and estimate *magnitude* (i.e., Lourenco and Longo, 2011; Notebaert et al., 2011; Linsen et al., 2015; Lyons and Ansari, 2015). The brain also rotates shapes (i.e., Harris and Miniussi, 2003; Frick et al., 2013; Thompson et al., 2013; Bruce and Hawes, 2015), and understands the role and meaning of *place value* (i.e., Butterworth et al., 2011; Ferguson, 2015; Lambert and Moeller, 2019).

Yet other research clarifies the neural networks related to the role of fixed *sequence* (Grafton et al., 1995; Orban et al., 2011; Kidd et al., 2012; Pariyadath et al., 2012), and how the brain determines a general sense of *numerosity* (i.e., Piazza et al., 2004, 2006; Xu et al., 2005;

TABLE 1 Examples of differences in the math literature between educational curriculum and neuroconstructivist design.

Early mathematics	
Educational curriculum (Observable, visible behavior)	**Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)**
Counting	• Decoding (e.g., Cho et al., 2011) • Discrimination and enumeration (e.g., Nan et al., 2006) • Distance and congruity (e.g., Kaufmann et al., 2005) • Finger counting (e.g., Soylu et al., 2018) • Inhibitory control and visual processing (e.g., Fan et al., 2014) • Number vs. non-number symbols (e.g., Zhang et al., 2012) • Numerosity (e.g., Zago et al., 2010; Hannula-Sormunen, 2015) • Sequential sensory and motor event (e.g., Kansaku et al., 2006) • Visual enumeration (e.g., Demeyere et al., 2012) • Numerical and non-numerical ordinality (Kaufmann et al., 2009; Lyons and Beilock, 2013)
Comparing and ordering	• Categories and concepts (e.g., Miller et al., 2003) • Format comparison (e.g., Olkun et al., 2015) • Number words vs. digits (e.g., Hung et al., 2015) • Number-size inference (e.g., Kaufmann et al., 2006) • Numerical analogical reasoning (e.g., Wu et al., 2016) • Numerical magnitude and working memory (e.g., Knops, 2006) • Numerical ordering and symbolic arithmetic (e.g., Knops and Willmes, 2014) • Ordinal representation (e.g., Attout et al., 2014) • Relational reasoning and symbolic distance (e.g., Hinton et al., 2010) • Semantic and perceptual processing of number symbols (e.g., Holloway et al., 2013) • Spontaneous focus on numerosity (e.g., Hannula-Sormunen et al., 2016) • Symbolic number comparison (e.g., Ansari et al., 2005; Mussolin et al., 2010; Goffin and Ansari, 2016)
Recognizing numbers and "subitizing"	• Difference between subitizing and counting (e.g., Yue-jia et al., 2004; Vuokko et al., 2013) • Difference between subitizing and estimation (e.g., Burr et al., 2010; Cutini et al., 2014) • Gestalt perception in visual quantification (e.g., Bloechle et al., 2018) • Multiple object individuation (e.g., Mazza and Caramazza, 2015) • Pre-attentive and serial processing (e.g., Piazza et al., 2003) • Tactile consciousness (e.g., Gallace and Spence, 2008)
Coding and codification	• Symbolic vs. non-symbolic number identification (e.g., De Smedt and Gilmore, 2011; Skagenholt et al., 2018) • Math, Letter and Other symbols (e.g., Cantlon et al., 2011; Grotheer et al., 2016) • Analogical thinking (e.g., Vendetti et al., 2015; Marchand and Barner, 2018; Park, 2020) • Abstract to symbolic to concrete (e.g., Donovan and Fyfe, 2019)
Composing numbers	• Approximate quantification categories (e.g., Gandini et al., 2008) • Number processing (e.g., Knops, 2017) • Quantifiers, numbers and numerosity (cardinality) (e.g., Wei et al., 2014; Goffin, 2019) • Roman vs. Arabic numbers (e.g., Masataka et al., 2007) • Triple code (e.g., Skagenholt et al., 2018)
Forms, shapes	• Part vs. Whole comprehension (e.g., Hallowell et al., 2015; Zambrzycka et al., 2017) • Shape descriptions (e.g., Dillon, 2017) • Shape identification (e.g., Scherf et al., 2009; Chen et al., 2021) • Shape reproduction (e.g., Williams et al., 2014) • Preliminary alignment (e.g., Ons and Wagemans, 2012; Fragaszy et al., 2015) • Shape mapping (e.g., Du et al., 2018)
Adding and subtracting	• Abacus mental calculation (e.g., Chen et al., 2006) • Adult vs. child arithmetic processing (e.g., Peters, 2016) • Arithmetic and language (e.g., Baldo and Dronkers, 2007) • Calculation (e.g., Davis et al., 2009) • Manual calculation (e.g., Masataka et al., 2006) • Mental arithmetic (e.g., Artemenko et al., 2018) • Mental calculation (e.g., Gruber, 2001) • Number sense (e.g., Dehaene et al., 2004) • Simple calculation (e.g., Zago et al., 2001) • Symbolic and non-symbolic arithmetic (e.g., Venkatraman et al., 2005)

(Continued)

TABLE 1 (Continued)

Early mathematics	
Educational curriculum (Observable, visible behavior)	Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)
Multiplying and dividing	• Component processes of inductive reasoning (e.g., Jia et al., 2011) • Developmental dissociation (e.g., Prado et al., 2014) • Error detection (e.g., Kroeger, 2012) • Fractionating and working memory (e.g., Metcalfe et al., 2013) • Mental calculation (e.g., Gruber, 2001; Hanakawa et al., 2003) • Naming actions versus naming spatial relations (e.g., Damasio et al., 2001) • Problem solving (e.g., Lin et al., 2015) • Problem-size effect (e.g., Prado et al., 2013) • Working memory (e.g., Metcalfe et al., 2013)
Measuring	• Number-size interference (e.g., Kaufmann et al., 2006) • Numeral classifiers (e.g., Cui et al., 2013) • Numerical distance effect (e.g., Mussolin et al., 2013) • Perceptual similarity (e.g., Axelrod et al., 2017) • Quantity processing of quantifiers, numbers, and numerosity (e.g., Wei et al., 2014) • Repetition and regularity (e.g., Dehaene et al., 2015) • Attributes (e.g., Vingerhoets, 2008; Clements et al., 2022) • Comparisons (e.g., Kaufmann et al., 2006)
Naming geometric shapes	• Description (e.g., Dillon, 2017) • Identification (e.g., Benischek, 2018) • Features of (e.g., Biederman, 2013) • Meaning making (e.g., Voss et al., 2010) • Naming and spatial relations (e.g., Damasio et al., 2001) • Object-based attention (e.g., Ongchoco and Scholl, 2019) • Shape-form shading (e.g., Hou et al., 2006) • Unfamiliar shapes (e.g., Voss and Paller, 2010) • Visual perception (e.g., Pollen, 1999) • Visual context (e.g., Ejima et al., 2007) • Visual search (e.g., Fockert et al., 2004)
Ordinal(ity)	• Fixed order (e.g., Rubinsten et al., 2013) • Unique (e.g., Lyons et al., 2016) • Relative (e.g., Attout et al., 2014) • Counting out loud (e.g., Gordon and Ramani, 2021) • Rank (including before and after) (e.g., Nieder, 2005) • Inverse (e.g., Berch et al., 2016) • Sequence (e.g., Hedenius et al., 2013; Steinemann et al., 2016) • Place value (e.g., Varma et al., 2008; Möller, 2010; Kraut and Pixner, 2023)
Comparing geometric shapes	• Eye tracking (e.g., Verdine et al., 2017) • Haptic to visual (e.g., McLaughlin, 2000) • Letter matching (e.g., Fecteau and Enns, 2005) • Name and shape matching (e.g., Monaghan and Pollmann, 2003) • Multi-sensory processing (e.g., Hulme et al., 1987) • Muscle movement and tracing (e.g., Portnoy et al., 2015) • Small and to-scale figures (e.g., Snapp-Childs et al., 2018) • Spatial rotation (e.g., Knouse, 2006) • Tracing and copying (e.g., Bernbaum et al., 1974) • Visual processing in haptic representation (e.g., Kalenine et al., 2011)
Composing geometric shapes	• Manual imitation (e.g., Braadbaart et al., 2012) • Motor control (e.g., Palmis et al., 2017) • Motor expertise (e.g., Calmels, 2020) • Object categorization (e.g., Athanasopoulos and Casaponsa, 2020) • Object vs. spatial imagery (e.g., Kozhevnikov and Blazhenkova, 2013) • Spatial rotation (e.g., Judd and Klingberg, 2021) • Tactile memory (e.g., Gallace and Spence, 2009)

(Continued)

TABLE 1 (Continued)

Early mathematics	
Educational curriculum (Observable, visible behavior)	Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)
Classifications	• Characteristics (e.g., Augustine et al., 2015) • Sets (e.g., Li et al., 2021a,b)
Spatial sense and motion	• Child vs. adult (e.g., Kucian et al., 2007) • Manual training (e.g., Wiedenbauer and Jansen-Osmann, 2008) • Motor development (e.g., Jansen and Heil, 2010) • Sex difference (e.g., Hahn et al., 2010) • Experience (e.g., Hertanti et al., 2019) • Working memory to visuomotor learning (e.g., Anguera et al., 2010) • Two- and three-dimensional shapes (e.g., Neubauer et al., 2010)
Patterning and early algebra	• Alphanumeric equations (e.g., Lee et al., 2007) • Core number systems (e.g., Abreu-Mendoza et al., 2020) • Gesture-based instruction (e.g., Wakefield et al., 2019) • Insight and ordinary problem solving (e.g., Lin et al., 2021) • Math symbols and numbers (e.g., Zhang et al., 2012) • Mathematical mindsets (e.g., Daly et al., 2019) • Pattern analysis (e.g., Johnson et al., 2009) • Relationship of words to math (e.g., Bates et al., 1992) • Strategies (e.g., Rosenberg-Lee et al., 2009) • Rhythmic patterns (Bergeson and Trehub, 2006) • Patterns in music (Geist et al., 2012)
Classifying and analyzing data	• Concept processing (e.g., Ghio, 2013) • Error detection (e.g., Kroeger, 2012) • Object recognition (e.g., DiCarlo et al., 2012) • Syntactic classification (e.g., Forkstam et al., 2006)
Equivalencies	• Spatial-numerical (e.g., Hubbard et al., 2009) • Matching (e.g., Emerson and Cantlon, 2012) • Reproduction (copying) (e.g., Gerván, 2012) • Decomposition (equivalencies) (e.g., Rosenberg-Lee et al., 2015; Xu and LeFevre, 2016) • Division (e.g., Ellis, 2015; Meng and Moriguchi, 2021) • Fractions (e.g., Wortha et al., 2020)
Approximations or estimations	• Calculation (e.g., Gunderson and Hildebrand, 2021) • Spatial orientation (e.g., Sutton et al., 2010; Cheng et al., 2013) • Spatial rotation (e.g., Newcombe et al., 2013) • Length, weight and quantity (e.g., Siegler and Booth, 2004)

Domahs et al., 2010; Anobile et al., 2013). These overlap but are distinct from neural networks related to *approximations*, *estimations* (Gilmore et al., 2014; Kibbe and Feigenson, 2015), and *equivalencies* (Mix, 1999; Hunt, 2011; Price et al., 2013; Chesney et al., 2014). There is also extensive work describing the brain and how it comprehends *arithmetic*, including division (i.e., LeFevre and Morris, 1999; Fehr et al., 2007; Grabner et al., 2009; Ischebeck et al., 2009; Andres et al., 2011; Rosenberg-Lee et al., 2011; Venneri and Semenza, 2011; Bugden et al., 2012), and grasps *proportions* (i.e., Sophian, 2000; Jacob et al., 2012).

Teachers can turn this list of neural pathways for math into useable knowledge in three ways. First and foremost, teachers can embrace the complexity of the brain and the sheer number of pathways involved in learning and resisting simplistic formulas for teaching and learning. Second, teachers can learn how observable behavior maps onto different types of neural networks which will help them better diagnose learning problems or gaps in student knowledge. And third, by understanding that different neural pathways are stimulated by different classroom and life experiences, they can select more efficient and effective learning interventions.

6.2.2. Neuroconstructivist language

Learning trajectories in language are similar to those found in math. In language, the four categories of networks were sub-divided by 16 neural networks that sub-divided into over 90 neural pathways. When matched with the educational literature, there were over 171 observable behaviors related to early language development.

To devise elements for the educational curriculum (left column in Table 2) studies from public policy, pediatrics, and literacy were combined. These studies span from the role of parents in pre-literacy development as correlated with social-economic status (Fernald et al., 2013), racial disparity (Hoff, 2013), current practices in nursery schools around the

TABLE 2 Examples of differences in the language literature between educational curriculum and neuroconstructivist design.

Language and pre-literacy	
Educational curriculum (Observable, visible behavior)	**Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)**
Receptive language	• Action observation (e.g., Marshall et al., 2011) • Auditory discrimination (e.g., Zhao et al., 2021) • Follows multiple-step instructions (good working memory) (e.g., Schneider et al., 2005; Yang et al., 2014) • Joint attention and understanding (e.g., Woodward, 2005; Saby et al., 2012) • Points to appropriate object on command (e.g., Melinder et al., 2015) • Responds to one word commands ("no") (e.g., Mestres Missé, 2007) • Speech perception and comprehension (e.g., Friederici and Männel, 2013) • Understands role of pointing (e.g., Gredebäck et al., 2010) • Semantic and syntactic sentence processing (Schneider and Maguire, 2019) • Speech discrimination and later grammar (Zhao et al., 2021) • Syntax (Klein et al., 2022)
Productive language	• Speech imitation (spontaneous) (e.g., Garnier et al., 2013; Kokkinaki and Vitalaki, 2013; Szczepek Reed, 2020) • Adjective generation (e.g., Zhang and Pylkkänen, 2018) • Affective contributions to lexical decisions (e.g., Sylvester et al., 2021) • First and second language speech (e.g., Petitto et al., 2012; Cristia et al., 2014) • From auditory to speech perception (e.g., Dehaene-Lambertz et al., 2005) • High frequency sounds, novel sounds (e.g., Gervain et al., 2016) • Human action sounds vs. other sounds (e.g., Geangu et al., 2015) • Intelligible speech (e.g., Khandaker, 2015; Friederici et al., 2017). • Morphology and syntax (e.g., Benavides-Varela and Gervain, 2017) • Noun generation (e.g., Schipke et al., 2012; Takashima et al., 2019) • Plurals and semantic numbers (e.g., Dunagan et al., 2022) • Sentence construction (e.g., Schneider and Maguire, 2019) • Syntactic processing (e.g., Oberecker et al., 2005) • Two-word sentences; three-word sentences (e.g., Werker and Vouloumanos, 2001) • Phonological processing (Powers et al., 2016) • Words and syntax (Takashima et al., 2020)
Vocabulary	• Meaning to object (point to correct picture) (e.g., Takashima et al., 2019) • Movement/gesture and vocabulary (e.g., Skoning et al., 2017) • Object-to-meaning (semantic memory) (e.g., Ferreira et al., 2015; Peeters et al., 2017) • Phonotactic processing (e.g., Steber and Rossi, 2020) • Social cues (e.g., Yu and Ballard, 2007) • Verbs vs. action verbs (e.g., den Ouden et al., 2009; Zhang et al., 2018) • Visual literacy and picture naming (e.g., Deetsch et al., 2018) • Word classification (e.g., Saccuman et al., 2006) • Gesture and semantic memory (de Marco et al., 2022)
Storytelling	• Alliteration (e.g., Pedott et al., 2017) • Audio vs. Illustrated vs. Animated (e.g., Hutton et al., 2020) • Beginning-middle-end (working memory) (e.g., Veraksa et al., 2020) • Gestures and visual support (e.g., Schaadt, 2015; Kartalkanat and Göksun, 2020) • Illustrations and visual support (e.g., D'Angiulli et al., 2015) • Intonation, prosody (e.g., Hupp and Jungers, 2013; List, 2019) • Lexical tone perception (e.g., Liang and Du, 2018) • Pitch and meaning (e.g., Morrill et al., 2015) • Prediction (e.g., Misyak et al., 2010; Lehne et al., 2015; Veraksa et al., 2019; Hasegawa et al., 2021) • Questioning (e.g., Frank et al., 2012; Schipke et al., 2012; Schouwenaars et al., 2018) • Rhythming (e.g., Wagensveld et al., 2013; Hurschler, 2015)
Alphabet	• Audiotactile processing (blind) (e.g., Pishnamazi et al., 2016) • Letters, symbols and digits (e.g., Carreiras et al., 2015) • Symbol vs. non-symbol recognition (e.g., Yamada et al., 2011) • Symbol-to-phoneme recognition (e.g., Katzir et al., 2005; Widmann et al., 2007)

(Continued)

TABLE 2 (Continued)

Language and pre-literacy	
Educational curriculum (Observable, visible behavior)	**Neuroconstructivist design (Invisible neural pathways that must be stimulated to produce visible behavior)**
Story generation	• Natural skill (e.g., Bers and Cassell, 2000) • Thought to text (e.g., Fayol et al., 2012) • Voice-to-text (e.g., Whitney et al., 2009; Fudickar, 2018; Siok and Luke, 2020; Romanovska et al., 2021)
Spelling	• Isolated impairment (e.g., Gebauer et al., 2012) • Lexicality (e.g., Weiss and Booth, 2017) • Misspelling (e.g., Purcell et al., 2011a) • Phonemic awareness (e.g., Katzir et al., 2005; Booth et al., 2007; Kemény et al., 2018) • Priming (e.g., Cao et al., 2010)
Morphology	• Prefixes and suffixes (Gao et al., 2023) • Morphological processing (Louleli et al., 2022)
Reading	• Fluid reading (e.g., Christodoulou, 2010) • Phonological processing (e.g., Orechwa, 2009; Cherodath et al., 2017) • Syllables to sentences (e.g., Friederici, 2005) • Concrete vs. abstract words (D'Angiulli et al., 2015) • Silently vs. aloud (Xia et al., 2018) • Universal reading network (Feng et al., 2020) • Audio-visual integration (Li et al., 2023) • Functional reading network (Benischek et al., 2020)
Sight words	• Rapid naming (e.g., Misra et al., 2004; Saletta, 2019) • Phonological and semantic processing (Mathur et al., 2020)
Sentence construction	• Sentence reading (e.g., Simos et al., 2011) • Transcription vs. writing (e.g., Wallis et al., 2017) • Syntax and semantic overlap (Fish, 2020)
Text	• Capital vs. small letters (e.g., Dehaene and Cohen, 2010; Augustine et al., 2015; Jung et al., 2015) • Fonts (e.g., Vinci-Booher and James, 2020; Fabiani et al., 2023) • Handwriting vs. print text (e.g., Longcamp et al., 2006; Downey, 2014; Roux et al., 2021) • Mirror reading (e.g., Dehaene et al., 2010) • Print vs. cursive (e.g., Gilet et al., 2011)
Handwriting	• Drawing pictures for meaning (e.g., Gansler et al., 2011; Schlegel et al., 2015; Yuan et al., 2018) • Geometrical shapes to letter formation (e.g., Norton, 2012) • Haptic memory (e.g., Gallace and Spence, 2009) • Motor control (e.g., Simiona, 2016; Palmis et al., 2017) • Tablet versus handwriting (e.g., Lin et al., 2021) • Word shapes and hand gestures (e.g., Nakamura et al., 2012)
Writing	• Symbol systems (Li et al., 2021a,b) • Central and peripheral processing (Purcell et al., 2011b) • Orthographic loop (Richards et al., 2012) • Imagined writing (Baumann et al., 2022) • Global networks of good vs. poor writers (Costa et al., 2022) • Visual-motor networks (Vinci-Booher and James, 2021) • Differences of pencil, keyboard, tablet (Mayer et al., 2020)

world (Halden et al., 2011); and the ways that literacy parallels other milestones in growth (Hoff, 2009). Furthermore, there is documentation of the natural ordering of language skills in children 0–6 (Luinge et al., 2006) described as a natural hierarchy of pre-literacy skills. Literacy understanding from the contributions made by research from second language learners (e.g., Kuhl, 2011) as well as that from language learning delays caused by congenital defects and in cases of autism (McDuffie and Haebig, 2013) have also highlighted the core notions underpinning successful language acquisition. As with Tables 1, 2 right-hand column is comprised of a representative sampling of the various sub-skills or core notions needed to achieve the educational curriculum indicated in the left column.

This sampling of the many pathways found within the networks makes the precision of their activation more targeted than general guidelines found in education. For example, educators often talk about "language problems," whereas a neuroscientist might speak about the precise problem of semantic memory, non-letter symbols used in reading, or the way that prosody influences meaning.

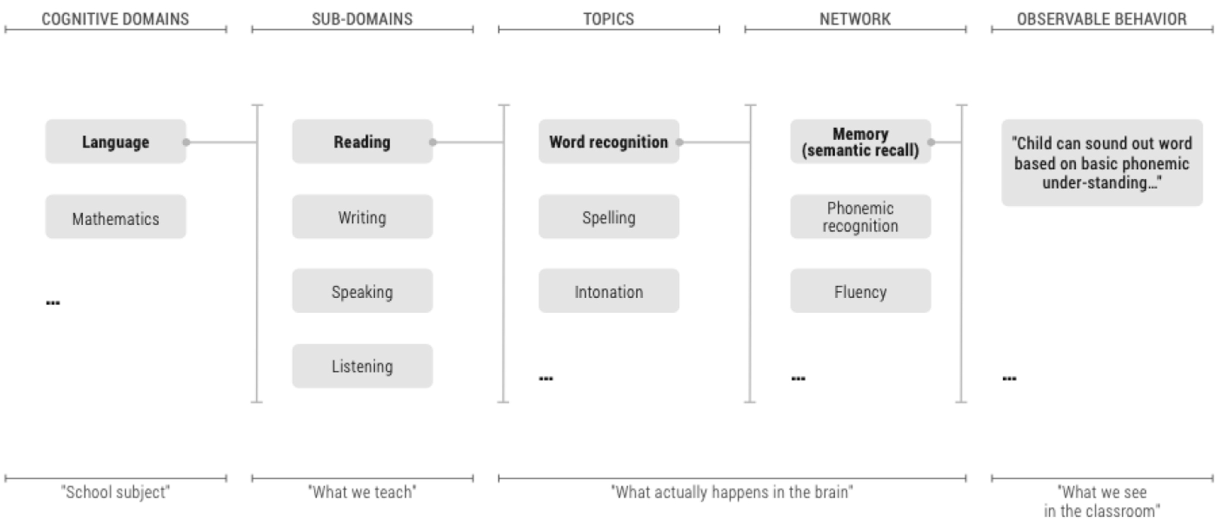

FIGURE 4
From academic domains to the brain and back.

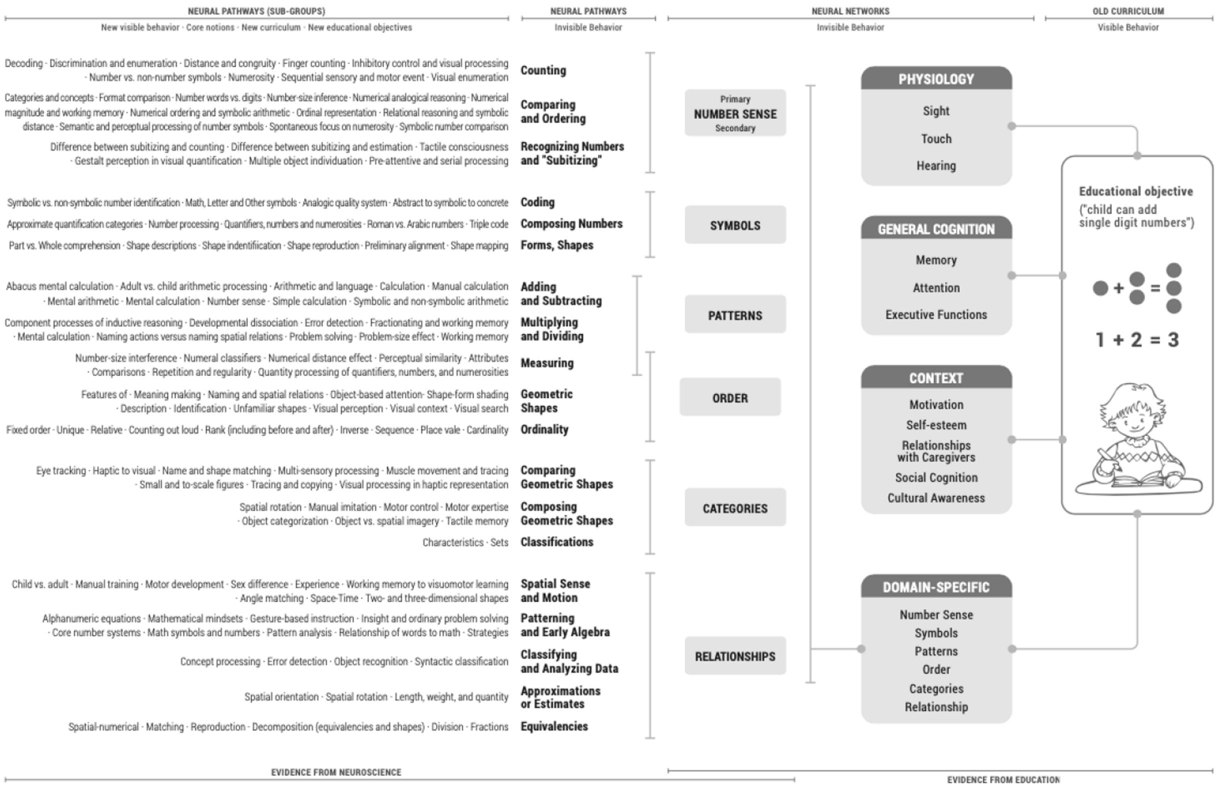

FIGURE 5
From invisible core notions to the visible educational curriculum.

Educators can learn from neuroscientists as the more precise the diagnosis, the better, more accurate the cure. That is, if a teacher know the "language problem" is one of symbol-to-sound (phoneme) difficulties, they will use a different intervention than if the problem is one of semantic retrieval.

The domain-specific areas of math and language were subdivided into (a) innate sense (i.e., innate number sense; innate language sense), (b) symbols, (c) patterns, (d) order and (e) categories, and (f) relationships.

One way to use the terminology from Education and Neuroscience together is in Figure 4.

To display a transdisciplinary understanding of early math and pre-literacy, it is necessary to travel from visible behavior to invisible neural networks, as seen in Figure 5.

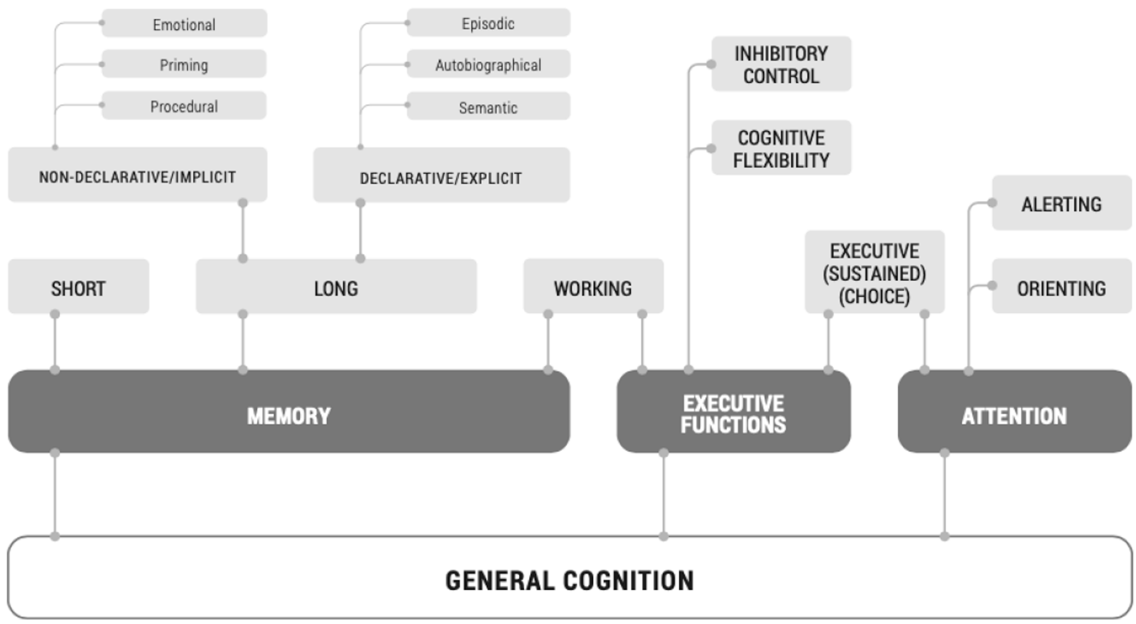

FIGURE 6
Neural pathways within the general cognition networks.

The domain specific neural networks for math and language are important when students encounter problems limited to those subject areas. If the student has both math and language problems, however, it is more likely than not that the student has a general cognitive network problem (Figure 6).

6.3. General cognition networks

All domain specific learning in math and language also depend on general cognition as well. General cognition is founded on two core pillars of learning: well-functioning (a) memory systems and well-functioning (b) attention systems (Tokuhama-Espinosa et al., 2020). Based on evidence from neuroimaging, both memory and attention make up (c) Executive Functions. Memory is sub-divided into complex (1) long-term memory, which in turn is divided into (i) non-declarative and (ii) declarative, (2) working memory, and (3) short-term memory. Executive Functions are sub-divided into (1) working memory, (2) cognitive flexibility, and (3) inhibitory control. Attention is sub-divided into (1) executive or sustained attention, (2) alerting, and (3) orienting systems (Fan and Posner, 2004). Just as each network in the domain specific areas of math and language sub-divide into numerous neural pathways (core notions), so do general cognitive networks. For example, long-term declarative memory networks can be further divided into semantic, autobiographical and episodic memory pathways, and there are likely many more.

6.4. Context networks

It is now commonly accepted that the context within which one learns influences the learning itself (National Academies of Sciences, Engineering, and Medicine, 2018). The literature review revealed studies of learning context related to the role of (a) social contagion in learning, how (b) relationships with caregivers influenced learning, the role of (c) self-esteem in learning, and how (d) motivation impacts learning (Figure 7). These pathways, in turn, were sub-divided even further. For example, social contagion (a) was viewed differently in studies related to (1) cultural awareness and context as compared with (2) theory of mind research.

6.5. Sensory networks

All learning occurs through the senses, as Aristotle pointed out over 2,500 years ago. Without sensory perception no learning is possible, let alone math and language. Hearing, Sight, and Touch studies were included in the review. Smell and taste were less prevalent in both the neuroscientific and educational literature and were therefore not included though future studies should consider their possible roles in learning math and language (Figures 8–10).

There are 10 identifiable pathways that emerge from the Hearing network, including distinct pathways for (a) pitch, (b) tempo, (c) tone, (d) prosody, and (e) loudness. Related to orientation within hearing were two distinct pathways related to echolocation or sounds that come from the (f) left versus right and from (g) foreground versus background sounds. Other pathways relate to the integration of sight and hearing through the interpretation and use of (h) hand gestures to support auditory compression. It was also found that the brain perceives and interprets (i) human voices distinctly from other sounds. Finally, there were multiple studies on (j) auditory processing, which combined sensory, motor, memory, and attention sub-systems.

Within Vision, it was found that there are 11 distinct pathways including those for (a) color, (b) luminance, (c) size, and (d) proximity.

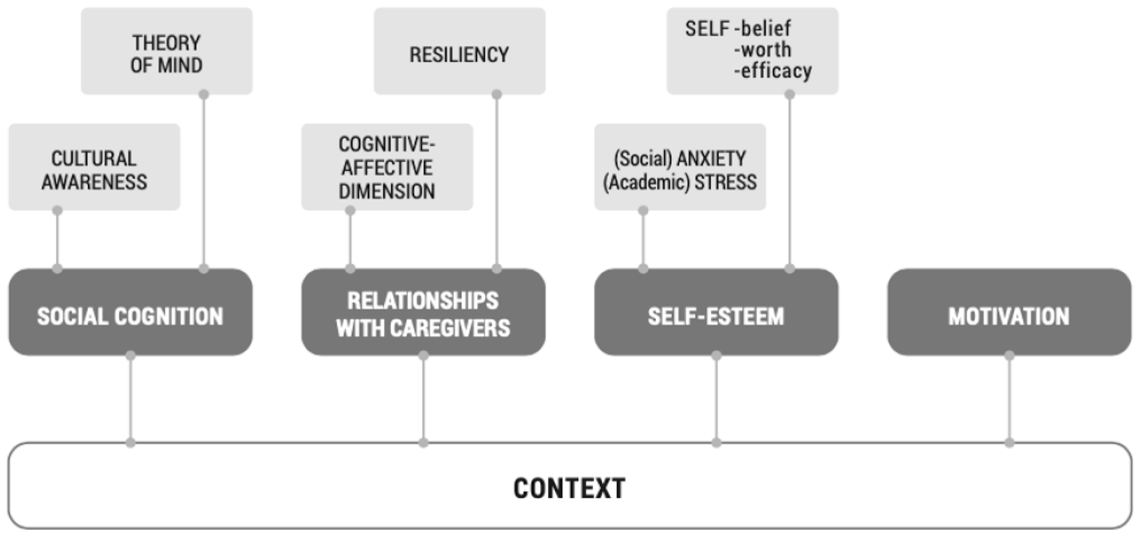

FIGURE 7
Neural pathways within the context network.

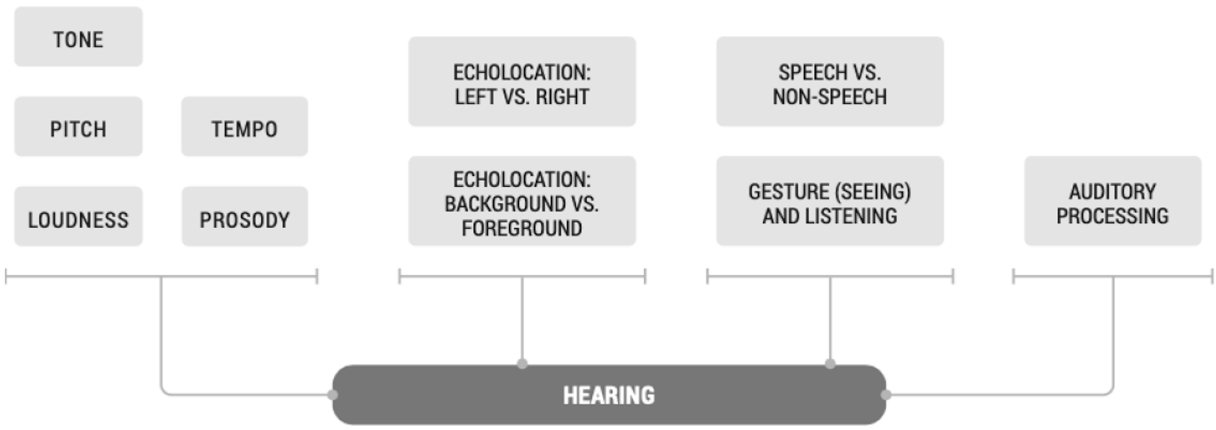

FIGURE 8
Neural pathways within the hearing network.

Visual pathways also distinguish (e) perception vs. action, (f) motion, and (g) spatial–temporal contrast. It was also found that as the most studied human sense, (h) visual crowding, occupies a distinct neural pathway from (i) spatial frequency, which is also distinct from the brain's ability to search and determine (j) saliency in its surroundings. Finally, after 40 years of debate, it appears clear that the brain distinguished (k) human faces from other objects (Burns and Bukach, 2019).

The sense of Touch involves at least seven different neural pathways, but as the least studied of the senses, it is likely that additional research may extend these findings related to haptics and perception. There are distinct neural pathways for (a) visual motor integration, (b) scribbling, (c) fine motor tracing, and the (d) tactile recognition of shapes. Additionally, (e) writing—distinct from scribbling—(f) drawing, and the understanding of the (g) variant expressions of writing (such as capital versus small letters and cursive versus print, as well as different font forms) are also in distinct neural networks.

Of the four types of neural networks (domain specific, general cognitive, context, and sensory), sensory networks have the most research and the longest history. The sensory networks are based on perception from outside stimuli and memories of stimuli. Sensory networks were the gateways into the other three categories of networks. All four network categories are vital for learning to occur and should become part of teachers' knowledge. We suggest that sharing these 16 neural networks in teacher training can potentially improve teacher diagnosis of learning problems by increasing their nuanced understanding of "language problems" or "math problems" and relating them to the core notions of these subjects.

7. Discussion

On the basis of evidence from the learning sciences, we present a novel theory called Radical Neuroconstructivism, which is supported by extensive research from psychology, neuroscience, and education (Von Glasersfeld, 1984, 1995, 2013; Westermann et al., 2007, 2011; Dekker and Karmiloff-Smith, 2011; Hitchcock, 2018; Karmiloff-Smith et al., 2018;

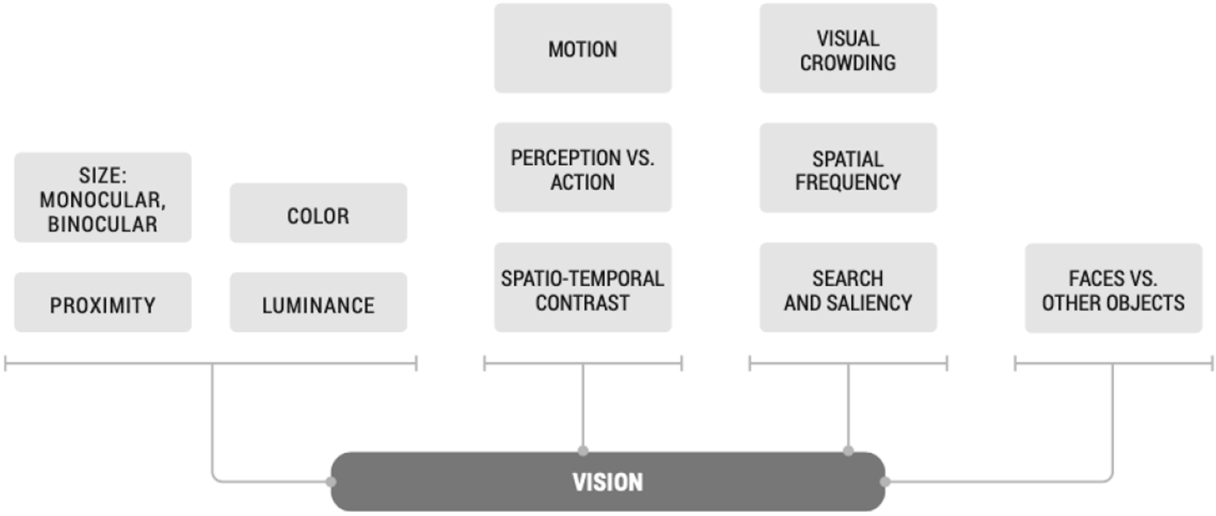

FIGURE 9
Neural pathways within the vision network.

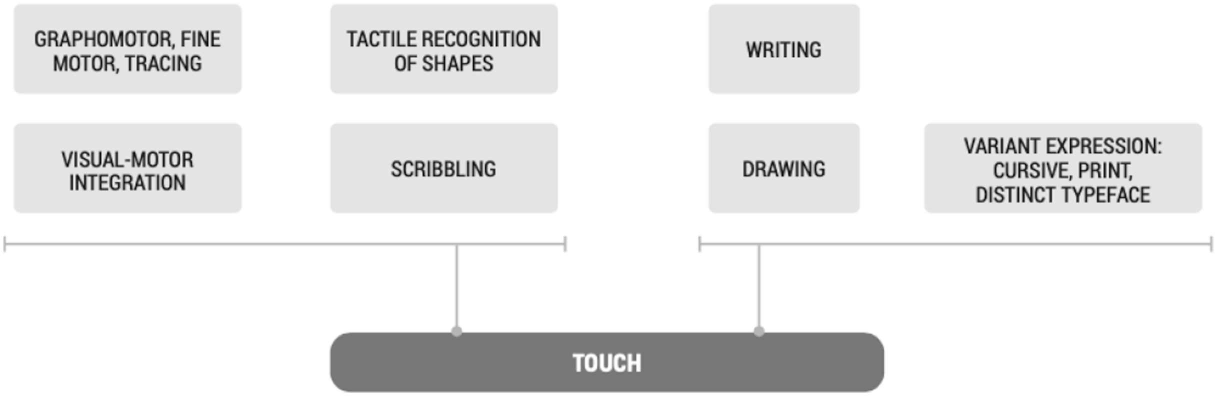

FIGURE 10
Neural pathways within the touch (haptic) network.

Broadbent and Mareschal, 2019; Tokuhama-Espinosa, 2019; De Soto, 2022). To further explain Radical Neuroconstructivism, we incorporate the concept of Meaning Making (Postman and Weingartner, 1969; Gay, 2018; Immordino-Yang and Knecht, 2020; Nouri et al., 2022) and Core Notions as the fundamental building blocks of cognition (Skerry and Saxe, 2016; Rist, 2017; Hernández Armenta et al., 2019; Solis-Stovall, 2020; Tuominen and Kallio, 2020; Sporns, 2022). We also provide examples of Math and Language learning trajectories that can be designed using neuroconstructivist principles, with more than 100 sources supporting each trajectory. Each of these studies holds individual significance and, when synthesized, we consider them to establish a powerful foundation for the proposed theory. We propose that the theory of Radical Neuroconstructivism offers a new framework for teacher education.

We suggest that teacher education can be seen as a holon, a complex system that consists of different parts that are interrelated and interdependent. However, not all parts of this system have received equal attention from academic disciplines such as psychology and education. While the question of *how* to teach has been widely researched, followed by the question of *what* to teach, the *why* of teaching has been less explored. This is where Mind, Brain, and Education (MBE) science can offer valuable insights. In Figure 11, in the first panel (Figure 5 "From Invisible Core Notions to the Visible Educational Curriculum"), the child learns the core notions in their own brain, but that same child (second panel) interacts with other children and the teacher. This dynamic exchange in the classroom is combined with the genetics, social-economic status and cultural context of the learner (third panel).

Evidence from MBE science can integrate the different subparts of teacher education by providing a better understanding of the *why*, which has been often neglected in traditional educational and psychological approaches. Radical neuroconstructivism is one framework that can inform teachers' professional development and complete the holonic perspective of teaching.

In relation to the *how* of teaching, radical neurosconstrutivism suggests that teachers should encourage active exploration and

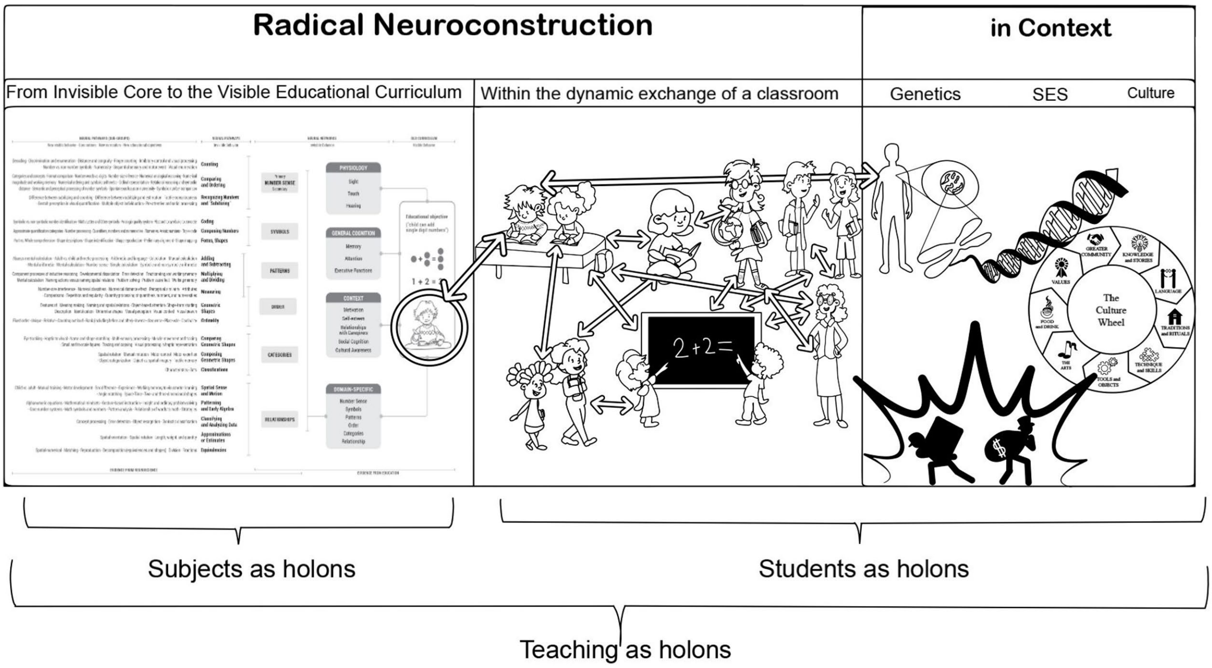

FIGURE 11
Radical neuroconstructivism in context.

discovery in their students, rather than transmitting information passively. This approach allows students to engage with the material in a meaningful way, and to construct their own representations based on prior knowledge and experience. Evidence as to why this is important suggests that active exploration can improve students' motivation, curiosity, creativity, and memory retention.

Regarding the *what*, radical neuroconstructivism suggests that teachers should be aware of students' developmental trajectories and individual differences, and tailor instruction accordingly. Teachers should identify difficulties and provide appropriate scaffolding and support to help students overcome them. Moreover, teachers should integrate different domains of learning in their curriculum to facilitate the formation of more abstract and generalizable representations, as well as the transfer of skills and knowledge across contexts.

To extend this perspective to the *why*, teachers need a solid understanding of core notions and the trajectories through which neural networks are constructed. This approach improves the order of skill acquisition by using a neuroconstructivist hierarchy, which may help create a more orderly curriculum built on insights from MBE science. Compared with MBE advancements from 2007 to present, by integrating research from neuroscience, psychology, and education, this new idea has the potential to inform the design of curriculum and instructional strategies that not only consider the what and how of teaching, but also the why, ensuring alignment with the brain's natural learning processes.

In conclusion, MBE science offers a hol(on)istic perspective on teacher education that takes into account the *what*, *how*, and *why* of teaching and learning. Radical neuroconstructivism is a useful framework for organizing teachers" professional development and applying insights from MBE science into curriculum design and instructional strategies. By using MBE science to inform teaching practices, teachers can create a more effective and engaging learning environment for students.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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Conflict of interest

Authors TT-E and CB provide consultancy services via the Conexiones platform. Author CB is employed by The Decision Lab.

Publisher's note

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