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Review article

Connecting levels of analysis in educational neuroscience: A review of multi-level structure of educational neuroscience with concrete examples

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ABSTRACT

In its origins educational neuroscience has started as an endeavor to discuss implications of neuroscience studies for education. However, it is now on its way to become a transdisciplinary field, incorporating findings, theoretical frameworks and methodologies from education, and cognitive and brain sciences. Given the differences and diversity in the originating disciplines, it has been a challenge for educational neuroscience to integrate both theoretical and methodological perspectives in education and neuroscience in a coherent way. We present a multi-level framework for educational neuroscience, which argues for integration of multiple levels of analysis, some originating in brain and cognitive sciences, others in education, as a roadmap for the future of educational neuroscience, with concrete examples in mathematical learning and moral education.

1. Introduction

Educational neuroscience is a vast and emerging field that incorporates methods and perspectives from brain and cognitive sciences, learning sciences, and educational psychology, among others. In its origins educational neuroscience started as an initiative to discuss implications of neuroscience findings for education. Going back as early as 1970s, these discussions focused on if it was at all meaningful to interpret neuroscience findings for education, and if so, for which specific issues and problems in education neuroscience findings have implications for.

So far, educational neuroscience has been acting as an interdisciplinary platform where two distinct fields, neuroscience and education, interact. The main theme that characterizes the field is the interpretation of neuroscience findings for educational research and practice, and increasing neuroscience literacy within the education community to diminish the negative impacts of neuromyths. But as a burgeoning transdisciplinary field, educational neuroscience is in the process of defining its major questions, methodologies, and theoretical frameworks, in addition to forming a community of scientists. As is historically typical of fields that shift from interdisciplinarity to transdisciplinarity, one challenge it is facing is incorporating the diverse research methodologies and paradigms from its parent fields such as education, cognitive sciences, learning sciences, psychology, neuroscience, and many others in an integrated way to address a unified set of research questions. This requires connecting distinct research methodologies functioning at different levels of analysis and coming from different theoretical orientations.

We argue that responding to the challenge of incorporating diverse research methodologies and levels of analysis is a crucial next step for the burgeoning field of educational neuroscience. Here, we first discuss some of the challenges facing educational neuroscience, present the levels of analysis traditionally associated with each field, and discuss the need to connect these levels so that educational neuroscience can emerge as an established transdisciplinary field with its own unique approach to research that distinguishes it from other fields of educational and brain sciences. To exemplify how the multi-level approach presented here applies to educational neuroscience, we present research studies on moral decision making and mathematical learning and cognition as examples for how educational neuroscience research can connect different levels of analysis, from classroom interventions to imaging studies. We present how findings, knowledge, and insight acquired from each of these studies address a set of central and unified research questions, allowing a multi-level transdisciplinary conceptualization of learning and cognition in each domain. Our expectation is that the framework and the case studies presented here will help with responding to concerns about the viability of educational neuroscience as a field.

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2. Criticisms of educational neuroscience

Before discussing how to link different levels of analysis in educational neuroscience, it is important to visit criticisms of educational neuroscience to pinpoint how the presented approach addresses current issues in the field. Even though discussions on the implications of brain science for education have been going on for decades [1,2], efforts that can generally be framed under educational neuroscience (or variably *mind, brain, and education)* still invoke skepticism. Skeptics point to philosophical and methodological differences, and lack of clear connections between neuroscience and education. Proponents are more optimistic and point to domains where brain science findings shifted perspectives and influenced teaching practices in education (e.g., reading, mathematics). In this section we visit some of the main criticisms of educational neuroscience and discuss the extent to which these criticisms were addressed.

Twenty years ago in an influential article Bruer [2] argued that bridging neuroscience and education is a challenge, and that neuroscience findings do not really have any direct and meaningful implications for education. He presented numerous examples for how misled excitement about bridging neuroscience and education are grounded in the misinterpretation and simplification of neuroscience findings, including synaptogenesis, critical periods in development, and beneficial effects of enriched environments on synaptic growth in rats. He argued that while it is not possible to directly bridge neuroscience and education, the two can be linked through mediation of cognitive psychology. From his perspective, neuroscience findings can only be meaningful for education if it goes through the interpretive filter of cognitive psychology. Even though it has been 20 years since the publication of Bruer's paper, his criticisms continue to be endorsed in more recent publications. For example Bowers [3,4] argued that it is psychological science that provides a scientific grounding for education, and neuroscience rarely provides any direct insights into learning and teaching. In addition, Bowers argued that behavioral measures are superior to neural measures in characterizing children's learning and cognitive processing; for example, when deciding whether remedial instruction should target underlying deficits or instead focus on the development of non-impaired compensatory skills.

As a response to Bowers' criticisms, Gabrieli [5] pointed out that, much like cognitive or affective neuroscience, educational neuroscience is a basic science that provides mechanistic accounts for functional organization of the brain. Even though educational neuroscience findings do not directly prescribe strategies to use in the classroom, there are numerous examples (e.g., reading, mathematics) for how educational neuroscience research informs mechanisms of learning and cognition in exceptional children, and provides insights into individual differences. Gabrieli presented a model where applied research, involving intervention studies, mediates the communication between basic research and classroom practice, where successful interventions are scaled. Gabrieli presents examples for how basic research findings on dyslexia, ADHD, autism and other conditions changed our understanding of the mechanisms underlying these conditions and inspired interventions with some promising results.

Howard-Jones et al. [6] separately responded to Bowers' criticisms. They likened the relation between neuroscience and education to how molecular biology is related to drug discovery. While the basic science provides insights about "where to look," it "does not prescribe what to do when you get there" (p. 7). The knowledge about neural correlates of cognition, and how typical and exceptional groups differ need interpretation through a pedagogical lens to develop interventions guided by basic research. Only after these interventions are tested through large-scale implementation studies (which are similar to clinical trials in medicine) do we have the type of knowledge that is directly applicable to classrooms. In response to Bowers' [4] argument that psychological level explanations are more relevant to education than neuroscience, Howard-Jones et al. pointed out that these two levels do not constitute a duality since the "neuroscience" in educational neuroscience is almost always a reference to cognitive neuroscience. Psychological and neural explanations are in fact complementary, and, like cognitive neuroscience, educational neuroscience connects these two levels.

The tension between the two levels of explanations, neural (or more broadly, biological) and psychological (which actually includes multiple sub-levels such as behavioral, cognitive, and socio-cultural) often come up in discussions about the goals and the future of educational neuroscience. Howard-Jones et al. [4] describe the goal of educational neuroscience as using "multiple levels of description to better understand how students learn, informed by changes at both behavioral and neuronal levels that are associated with such learning" (p. 6). However, critics of educational neuroscience point to the concerning trend for biological explanations having wide appeal among educators, often leading to neuromyths or simplistic and misleading interpretations of neuroscience findings, some of which are used to justify curricular reform [7–9]. Even though there is considerable enthusiasm in characterizing the interaction between neuroscience and education as a "two-way street," suggesting a bi-directional and reciprocal interaction between the two communities of researchers and practitioners [10,11], Turner [7] argues that a two-way interaction does not reflect the current reality of educational neuroscience; instead neuroscience plays a more dominant role and the field is still mostly occupied with translating neuroscience findings for educational practice. Turner also contends that these efforts are not as fruitful as it is portrayed by proponents of educational neuroscience, due to methodological incompatibilities (e.g., use of unauthentic and non-contextual tasks, focus on group of averages instead of individual differences), and the challenges educationists face in understanding neuroimaging methods, which is necessary in making sense of the reported findings.

One pitfall of the collaboration between education and neuroscience is the possibility of biological-level explanations taking over the already existing explanations at the sociocultural, first-person (phenomenological), and cognitive levels. In its journey from the 1950s cognitivist era to the 21st century, educational research has moved from more reductionist, post-positivist approaches to post-structuralist, situated, and constructivist ones. While doing so, educational research has developed a sensitivity towards the contextual and situated nature of learning, first-person experiences (phenomenology) of the learners, and individual differences in learning approaches and predispositions to learning. One of the concerns with the introduction of a vast new knowledge base provided by neuroscience is the potential of narrowing down the already existing levels of explanations in educational theory by over-emphasizing the biological aspects of learning [12], which sometimes stands counter to more socio-cultural approaches. The long time tensions between contextual vs. decontextualized, qualitative vs. quantitative, and ungeneralizable vs. generalizable research in educational research [13] are re-instantiated with educational neuroscience. A segment of the education community sees the introduction of neuroscience in education as an invasion of biological reductionism. Thus, it is necessary to theorize about how educational neuroscience will function as a multi-level enterprise; one that not only incorporates neurocognitive explanations, but also retains established levels of explanation in education.

Apart from theoretical differences and differences in philosophical assumptions about the nature of learning, there is also a methodological divide between neuroscience and education. Research methods in neuroscience (e.g., EEG, fMRI, fNIRS) are complex and require extensive training before one can use these methods and interpret data. This makes understanding and interpreting findings a challenge for educators. The difficulties with understanding the methods also makes it a challenge to address neuromyths. For example, in fMRI studies the representation of "hot spots" can lead to the notion that there are distinct and isolated functional units, instead of statistical maps showing areas exceeding a, to some extent arbitrary, threshold [14]. Similarly, research methods in education can be foreign to neuroscience researchers. Qualitative and socio-cultural research traditions are typically not part of neuroscientists' training. Therefore, research results from such research can appear as irreconcilable with neuroscience findings. Conducting and interpreting educational neuroscience research requires interdisciplinary teams of researchers or individual researchers who have expertise in methods in both fields. Educational neuroscience also needs to find ways of developing theoretical frameworks that can accommodate these different research methodologies.

On one hand, neuroscience research, apart from neuropsychological case studies, seeks to construct generalizable knowledge on mechanisms of learning, cognition, and affect by way of using randomized trials from random samples. On the other, educational research mostly targets studying learning in context and developing better educational systems. In addition to explicating generalizable principles and heuristics, this requires an emphasis on understanding individual differences, the role of the environment, and the wider socio-cultural and political contexts in which learning takes place.

Here, we first explicate the need for a theoretical framework to allow linking different levels of explanation that can be considered under educational neuroscience. We present a multi-level theoretical and methodological framework for educational neuroscience. The framework incorporates levels of explanation and methodologies both from education and brain sciences. The purpose is to contribute to discussions on the major goals of educational neuroscience as a field, discuss which approaches can provide the ground for a fruitful transdisciplinary fusion of ideas and methods from relevant fields, and propose a theoretical scaffold that can amalgamate the multiple levels of inquiry. To exemplify how an educational neuroscience study that spans across multiple levels would look like, we present exemplary research studies spanning across the different levels of analysis introduced.

Educational neuroscience is often characterized as a bridge between neuroscience and education [15]. This metaphor implies that educational neuroscience acts as a medium where two distinct fields interact. Alternatively, educational neuroscience can be characterized as a new field that fills the gap between brain sciences and education [16]. This metaphor implies a burgeoning, transdisciplinary field, in close contact with other relevant fields, but with its own main research questions, theoretical paradigms, research methodologies, academic journals, and communities of researchers and practitioners associated with the field need to emerge. Currently there are only two academic journals (i.e., "Trends in Neuroscience and Education" and "Mind, Brain, and Education") and a relatively small number of graduate programs (fewer at the PhD-level) specifically dedicated to educational neuroscience. The bridge metaphor still seems to better characterize the current state of educational neuroscience. However, the fast-paced progression of the field poses a future vision that better matches the "filling the gap" metaphor.

There are two main characteristics of educational neuroscience that distinguish it from other fields within brain sciences. First, the purpose of educational neuroscience is not only to understand the brain mechanisms that underlie learning and cognition, but also to study how learning happens in authentic contexts and to design learning environments and programs based on what we know about learning. This requires incorporation of research paradigms from different fields of education and brain sciences.

Secondly, even though the name "educational neuroscience" implies an emphasis on neural-level investigations, educational neuroscience should be characterized as a transdisciplinary field that incorporates multiple methodologies and levels of explanation from both education and brain sciences. The main purpose here is not to push for neural level explanations or neuroscience methodologies as alternatives to established paradigms in education. Instead, the goal is to explore how existing paradigms of educational research can be complemented with paradigms in brain sciences to provide multi-level explanations for how learning occurs. These diverse levels of explanation, i.e., socio-cultural, first-person, behavioral, cognitive, evolutionary, neural, physiological, and genetic (Fig. 1), are grounded in different research traditions, some of them in education, others in cognitive and brain sciences. Educational neuroscience faces the challenge of theoretically connecting these levels to provide coherent, multi-level explanations for learning and informing educational practice and policy.

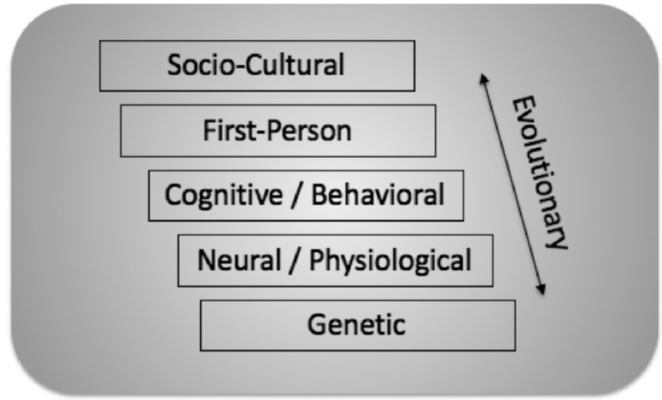

Fig. 1. Levels of analysis for educational neuroscience.

3. A Multi-level model for educational neuroscience

After Marr's influential work on distinct levels of analysis for information processing systems [17], it became common to approach cognition as a complex system that has multiples levels of organization [18]. Marr introduced three levels, computational, algorithmic, and implementation. The computational level describes the processes and operations conducted by the system. The computational level is about what the system does, but not about how it does it. The algorithmic level includes formal representations for the processes at the computational level. This level explicates how the system performs the operations described in the computational level. The implementation (or physical) level refers to the physical mechanisms that carries out computational processes. These physical mechanisms can be biological, silicon-based, or any other form of computational hardware.

Given that approaching cognition as a computational phenomenon became ubiquitous starting with the cognitive revolution in the 1950s, Marr's levels for information processing systems highly impacted our approach to cognition. However, the human cognition does not present an ideal match for the levels described in Marr's work. Marr proposed that these three levels can be analyzed independently; that we don't need to understand algorithms to study computations and implementation level to study algorithms. While the argument for independence neatly applies to computational systems (i.e., the same algorithm can be executed on different forms of hardware), its application to human cognition and neuroscience is problematic. Churchland and Sejnowski [19] argued that "the independence that Marr emphasized pertained only to the formal properties of algorithms, not to how they might be discovered" (pg. 742). There is no distinct, independent, and inherent algorithmic level in human cognition. The cognitive models we develop are mathematical formalisms describing the working principles of a system. The development of these models relies on studying the implementation (physical) level; biological and neural systems.

Churchland and Sejnowski [19] referred to three different types of "levels" in their discussion of cognitive neuroscience as an emerging field; levels of organization, levels of processing, and levels of analysis. Levels of organization refer to the different structural scales in which biological mechanisms can be studied. For the nervous system these include "molecules, synapses, neurons, networks, layers, maps, and systems" (pg. 742). All of these can be considered scales of structural organization under Marr's implementation level. Levels of processing describe the proximity of the information processed in a specific brain region to the original sensory input (e.g., in the visual cortex, neurons in the V1 area are at a lower level than the ones in the V3 area). Levels of analysis concern theoretical and conceptual divisions and the different questions that can be asked about a phenomenon.

We refer to the levels of analysis in our use of the term "levels." Cognitive neuroscience emerged as a result of the efforts to connect multiple levels of analysis. Previously, cognitive science had not been concerned with biologically grounding the information processing models developed. However, there came a point where the cognitive models had to be associated with what we know about the biological mechanisms in the nervous system, which led to the emergence of cognitive neuroscience as a field. As such, cognitive neuroscience encompasses behavioral, cognitive and biological levels of analysis, with different types of questions that can be asked under each. Churchland and Sejnowski argued that "it is difficult if not impossible to theorize effectively on these matters [related to nature of cognition] in the absence of neurobiological constraints" (pg. 744) and that understanding cognition requires connecting these interrelated, non-independent levels.

Educational neuroscience, like cognitive neuroscience, seeks to understand how biological mechanisms support learning and cognition, however educational neuroscience is additionally concerned with phenomenological (first-person), socio-cultural and contextual aspects of learning. As such, like cognitive neuroscience, educational neuroscience inherits levels of analysis from its parent fields; cognitive neuroscience and education. These levels are socio-cultural, phenomenological, cognitive, behavioral, and biological. The socio-cultural and phenomenological levels are unique to education, while biological is unique to cognitive neuroscience. Behavioral and cognitive levels are shared across education and neuroscience, because both fields are grounded on theories and findings from behavioral and cognitive psychology. We separate the biological level into two as neural/physiological and genetic, because the questions asked and methods used in these two levels are distinct, even though both concern biological mechanisms. A distinct evolutionary level is also included. In Fig. 1, a characterization of these levels is presented. Even though all levels presented in this model are interrelated, questions asked at the evolutionary level concern all the other levels. Evolutionary theories provide explanations for a wide range of phenomena, from cellular mechanisms to human social behavior, cutting across all other levels. Therefore, the evolutionary level is portrayed distinct from the others.

The hierarchical organization of the levels in Fig. 1 is based on how close the questions asked in each level are to the underlying biological mechanisms. In addition to the questions asked, these levels are also distinguished by research methodologies used. Below we present a short discussion of each level.

3.1. Levels of analysis in educational neuroscience

3.1.1. Socio-cultural level

At the sociocultural level, learning is defined as a situated activity taking place in a socio-cultural context [20]. Questions asked at this level concern how the socio-cultural context interacts with the learning process. A wide range of qualitative and design-based research methodologies are used. Research at this level takes place in authentic contexts.

3.1.2. First-person level

The inquiries at this level concern the direct experience of learners, reported by the learners themselves. It is closely related to the phenomenological tradition (e.g., [21]). This is a level that is relatively less valued by psychological and brain sciences, unlike education, where the learners' first-person experience is one of the main foci of study. Interviews, think-aloud activities, journals are some of the commonly used methods to study the first-person experience. There are also some non-mainstream approaches in brain sciences that explore how first-person experience can guide neural-level investigations (e.g., neurophenomenology [22,23]).

3.1.3. Cognitive/behavioral level

The cognitive and behavioral levels are intertwined and therefore considered together. The cognitive level involves the study of mental processes (e.g., memory, attention, perception) and development of mathematical and computational models of learning and cognition. Based on an information processing approach [24], cognition is characterized as processing inputs (perception) to produce outputs (action). Traditionally research in cognitive science had not been concerned with the biological correlates of cognition. With the emergence of cognitive neuroscience, the existing models in cognitive science were used to guide investigations on neural correlates of cognition. This is considered problematic and there are efforts in developing new cognitive models that are biologically constrained [25–27].

At the behavioral level the learning process is studied based on the observable behavioral indicators (e.g., reaction time, accuracy). There is an established tradition of behavioral science in psychology. Cognitive models are often assessed based on their ability to predict and model human behavioral performance. Behavioral data also accompanies and guides analysis of neuroimaging data in cognitive neuroscience studies.

3.1.4. Neural and physiological level

Perhaps, neural level explanations are the ones most emphasized in discussions about educational neuroscience. With fast-paced developments in neuroimaging technologies since the 1990s, neural level investigations have been pioneering psychological and brain sciences [28]. A wide range of methodologies is available to researchers (e.g., fMRI, Electroencephalography (EEG) / Event-Related Potentials (ERP), Magnetoencephalography (MEG), and functional near-infrared spectroscopy (fNIRS)).

Lack of ecological validity is a concern for most imaging and electrophysiological studies, because, due to methodological constraints, cognitive neuroscience studies often cannot use authentic tasks or take place in authentic contexts. For example, task designs in fMRI paradigms have to be structured in a way that the sub-processes take place in a pre-determined order, so as to capture and model the associated BOLD (blood-oxygen-level-dependent) response for each sub-process. Further, the context inside an fMRI scanner is quite different than an authentic context, where participants usually engage with the tasks used (e.g., classrooms). Lack of authenticity in the tasks and task-contexts raise questions about to the applicability of findings from neuroimaging studies for classrooms. However, there are some current efforts in developing new methodologies to conduct ecologically valid neural-level investigations (see [26,27]).

The physiological level refers to biological processes that are not considered a direct part of the central nervous system. These include measures like heart rate, cortisol level, and, electrodermal response (galvanic skin response). These measures are good indirect measures of the mental and emotional states of the participants in certain task conditions. Physiological measures are promising in studying student motivation and affect during learning in authentic contexts.

3.1.5. Genetic level

The genetic level concerns how genetic markers interact with cognitive abilities, neural and structural indicators, and performance. Research at this level mainly focuses on understanding cognitive and behavioral disorders, how genetic dispositions affect learning and how we can develop preventative or compensatory interventions [29].

3.1.6. Evolutionary level

Evolutionary explanations for human cognitive abilities often help make connections among human abilities, faculties, and phenotypes that would be hard to establish otherwise. Many of the human cognitive abilities (e.g., reading, mathematics) have taken their current form due to the recent cultural evolution and biological systems that support these skills have originally evolved to support other functions [30]. Therefore, interpreting neuroimaging findings and associating neural correlates of cognitive processes with other non-cognitive systems require an evolutionary approach. For example, there is extensive evidence showing that finger-based interactions play an important role in mathematical development and that neural correlates of mathematical cognition partially overlap with the finger sensorimotor system (see [31] for a review). When theorizing about the multi-modal systems supporting mathematical cognition, one has to consider antecedent systems that set the foundation for mathematical skills. Comparative studies with non-human animals, particularly primates, also provide key insights on the biological evolution of systems that support human cognitive skills (for example, see [32]). We position the evolutionary level distinct from others, since research questions related to evolution are studied across multiple levels, from genetic to socio-cultural.

Previously, Horvath and Lodge [33] proposed a model for “Science of Learning” (SoL), which included multiple levels of organization (from micro to macro); Cellular neuroscience → System neuroscience → Cognitive/behavioral neuroscience → Cognitive/behavioral psychology → Education (practice). Going back to Churchland and Sejnowski's [19] characterization of the three different types of “levels”, Horvath and Lodge's model is different from the model proposed here, in that our model concerns *levels of analysis*, while the former concerns *levels of organization*. Horvath and Lodge's argue for a similarity between levels-of-organization in biology (cellular → tissue → organ etc.) and their model; in both there is increasing complexity and different emergent phenomena across the different levels. These levels are argued to be incommensurable; they are separated based on the philosophical assumptions made, the research questions asked, and the methods used. The same is not true for the levels proposed here. The levels are not based on structural complexity and there is no containment hierarchy among them (e.g., cognitive/behavioral level does not include or contain the neural level). They are also highly interrelated and can be “commensurable.” For example, in the context of educational neuroscience, the genetic and neural/physiological levels usually concern behavioral and cognitive constructs (e.g., cognitive neuroscience), the cognitive and behavioral levels are interrelated (e.g., cognitive models are behavioral verified), and the evolutionary level involves providing evolutionary explanations for phenomena across all other levels, perhaps less so for the first-person level.

4. Challenges against ecological validity

There are two measures of ecological validity; veridicality and verisimilitude. Veridicality refers to how much the performance in a research study correlates with or predict real-world performance. Verisimilitude refers to the extent the cognitive processes involved in a research task resemble the ones involved in real-life contexts [34]. Both of these measures are particularly crucial for educational neuroscience studies, since a major goal of educational neuroscience is to have an impact on real-life contexts, such as classrooms. Typically, cognitive neuroscience studies take place in lab environments and use unauthentic tasks due to methodological constraints, which are both concerns for ecological validity. Educational neuroscience studies need to address these concerns. Improving ecological validity requires a reflection on both the tasks used and the contexts where educational neuroscience studies take place.

4.1. Experimental tasks

Tasks students are engaged with in the classroom and other real-life contexts are usually quite different than the tasks used in experimental research. In neuroimaging, the stimulus and task design is tailored to isolate and model distinct processes associated with the task studied. For example, in fMRI studies with arithmetic tasks, each trial usually includes a separate question presentation (e.g., “6 + 7 = “) and a validation (e.g., “15″) part, most often with fixed durations (e.g., [35]). The goal here is to separate the timing of processes associated with retrieval of arithmetic facts from other response-generation processes, which are not of interest. While this type of design allows modeling of the hemodynamic response related to retrieval of arithmetic facts, it leads to an unauthentic type of interaction, quite different from how students do arithmetic in real-life. Similarly, in most ERP studies involving a reading task, each word of a sentence is sequenced and presented separately with fixed stimulus durations, so that ERPs can be recorded separately for each word. This is necessary due to methodological constraints. A more authentic form, where the entire sentence is presented at once, would lead to more variance in the timing for reading each word and more noise due to eye-movements, and generating separate ERPs would require additional use of eye-tracking to determine the timing for when each word is read.

Experimental research requires averaging of data (both behavioral and neural) collected across many trials. The sequencing of trials from different conditions have to be controlled to avoid priming effects, or if a block-design is used, the order of the blocks should similarly be controlled. Both averaging of many trials of data across conditions and controlling for priming effects are difficult when an authentic task is used. In addition, the timing of each trial has to be controlled to ensure that similar numbers of trials are run across conditions and participants.

4.2. Experimental contexts

The major shortcoming of experimental lab studies for educational research is the lack of ecological validity. Learning takes place in dynamic, unpredictable and complex environments, such as the classroom. One aspect of this complexity is the rich social interactions taking place. A second one is related to physical situatedness; diverse forms of physical interactions taking place that wouldn't be possible in the lab environment. Authentic contexts are not conducive to experimental research both because random sampling is usually not an option (e.g., in school contexts), and neuroimaging and electrophysiological methods are hard to use in authentic contexts due to high-level noise induced by the dynamic environment, in addition to other practical contexts. However, there have been efforts in overcoming these difficulties, where, for example, EEG [36] and fNIRS [37] studies were conducted in not strictly controlled classroom contexts.

All of the constraints listed above lead to experimental tasks and task-contexts that are quite different than their real-life counterparts. These differences are of concern in regard to ecological validity. However, there are ways of addressing some these concerns with research designs improving ecological validity.

4.3. Research designs to improve ecological validity

Currently research that targets combining neuroscience and education approaches generally are more biased towards using neuroscience research methodologies to answer some of the previously unanswered questions in education. For example imaging studies on dyslexia have provided new insights on the neural mechanisms that underlie dyslexia, which then informed learning interventions that help address early phonological processing impairments [38]. However, implications of cognitive neuroscience studies informing educational design and practice does not fully exemplify the emergence of a transdisciplinary research field, connecting the aforementioned levels.

We need to take further steps to improve ecological validity and incorporate socio-cultural and first-person aspects of learning in educational neuroscience investigations. Below, we exemplify various research design approaches that incorporate perspectives, paradigms and research methodology from education and neuroscience. Our goal is to show the types of research designs that span across multiple levels of analysis. These methodologies represent varying degrees of integration between the two fields. The methodological approaches listed below are not mutually exclusive and most studies can employ more than one of these approaches.

4.3.1. Pre-test, intervention, post-test

The goal of this design is to test hypotheses related to the effectiveness of an educational intervention. This form of design allows for using authentic tasks in the intervention stage, with more traditional behavioral and neuroimaging tasks used during the pre/post-test stages. This form of design presents opportunities with collecting data spanning across multiple-levels. While the pre- and post-test stages can include traditional behavioral and neuroimaging tasks, the intervention stage can include authentic tasks. The data collected during the intervention stage can also capture the socio-cultural and first-person aspects of the learning process.

4.3.2. Classroom studies

Classroom studies involve collection of different forms of data using methodologies typically used in the lab. These can include, for example, EEG, eye-tracking, and interaction-logging. These forms of studies involve both authentic tasks and authentic contexts. Multiple studies have used EEG and fNIRS during classroom sessions [e.g., 36,37]. Difficulties with marking events with high level of temporal accuracy, artifacts and noise due to a wide range of concurrent modes of processing and bodily movement, and the impossibility of controlling the stimuli and sequencing of events in the complex classroom environment are some challenges.

4.3.3. Lab studies with authentic tasks

An authentic task is characterized by natural ways of interaction, where the sequencing of events is not pre-determined and one where the interactions afford a continuous experience, not interrupted by constraints typical to classical experimental designs (e.g., inter-trial intervals, short task trials targeting a single form cognitive processing). In this type of research design the primary goal is to overcome the lack of ecological validity in more traditional designs by using authentic tasks.

Given the constraints inherent to the neuroimaging methods [39,40] neuroimaging studies often do not use authentic tasks. One exception to this is neuroimaging research on video games [41] and methodological heuristics acquired from this body of research can be implemented in other research using authentic tasks. Previous neuroimaging research on video games has explored a wide range of phenomena including cognitive workload / mental effort, engagement / arousal, attention, spatial processing, emotion and motivation, as well as agency and perspective-taking [42,43].

4.4. Individual differences

Higher interest in individual differences has previously been listed as one of the qualities that distinguishes educational research from brain and cognitive sciences research [44]. For educational studies, understanding how individual differences affect learning experience and performance is of primary importance. In brain and cognitive sciences, the primary goal is usually to explore large patterns that characterize a sample, and individual differences, when investigated, are usually of secondary importance.

In an ideal world we would be able to conduct both ecologically valid and reproducible studies and develop learning theories encompassing all of the levels of analysis. In a less ideal world, our investigations and theories incorporate at least a large subset of these levels. However, most research explicitly focus on how learning occurs at one given level; such research might be a part of “educationally relevant neuroscience” rather than genuine “educational neuroscience.” One reason for this is the methodological difficulty of collecting and analyzing data at each level to develop a theory that relates all these levels. For example, ERP research requires collecting many trials of data for the same condition to reliably study the effect of a manipulation on a specific component [45]. In addition, EEG/ERP data collection requires subjects to be relatively steady, and even limit the most natural actions like eye-blinking, or head movements. These constraints make it hard to design authentic tasks, which would improve ecological validity. In addition, the lab environment is artificial and does not provide an authentic socio-cultural context. As mentioned before, there are attempts to overcome these challenges by using authentic tasks and using mobile neuroimaging devices to collect data in authentic environments, like classrooms [46–48]. There are also some efforts in using participants’ reported first-person experience as a guide, while analyzing behavioral and neural data [23,49]. These are promising efforts that are yet to mature and perhaps will become mainstream research methodologies in the future.

Both, the authenticity of the socio-cultural context as well as learners’ first-person experiences, are typically highly prioritized in educational research. In brain sciences, notions like reproducibility of empirical investigations, reliability and validity, and power of statistical results are important. These priorities reflect different epistemological assumptions and methodological constraints. Educational neuroscience is in need of finding a meeting ground that can accommodate these differences, even when some compromises are made. In its current state, educational neuroscience sometimes acts as a platform, where brain scientists share what they know about the brain and cognition with educators and discuss implications. This was previously called the “one-way model”. The desirable mode of interaction is one where there is a two-way communication [7,11]. The benefits of a multi-level approach extend beyond the scientific merits of investigating a phenomenon. It can also make findings about learning and cognition more accessible to application-based fields and stakeholders without compromising the science behind it.

Relating the previously discussed levels of inquiry is a challenge. Each level comes with a baggage of theoretical perspectives, research methodologies and “academic silos” separating the fields that each level is grounded in. There is need for a theoretical scaffold that can connect these levels. This theoretical scaffold should be able to accommodate explanations on how learning takes place across each level and integrate them to provide a coherent, multi-level explanation for learning and cognition. Because the levels of inquiry presented originate from different fields, there are also a wide range of theoretical perspectives presented. For example, the cognitive level is dominated by cognitivist theories, while the first-person level is closer to phenomenological traditions. As Marr famously observed, “Trying to understand perception by studying only neurons is like trying to understand bird flight by studying only feathers: It just cannot be done” [17]. The same is true for understanding bird flight through pure observational and behavioral data. In the same vein, learning in authentic contexts can be fully understood only through a combination of methodologies and perspectives [50,51].

The multi-level perspective empowers educators and acknowledges the fact that educational neuroscience is not a colonization of the educational landscape by knowledge and methodologies from neuroscience and other mediating disciplines, but rather various fields coming together to yield to the emergence of a new field, situated in between, where perspectives, methodologies and levels of explanation from each originating field is valued and used. To facilitate our understanding on how the multi-level aspects of educational neuroscience can contribute to the improvement in education, we review some previous studies that have attempted to connect the different levels and methodologies. We review these studies in order to exemplify how the multi-level approach can be implemented in educational neuroscience.

5. Examining the multi-level model with concrete examples in educational settings

In this section, we reviewed how the proposed conceptual framework for educational neuroscience can be implemented with concrete examples in diverse educational settings. The reviewed cases were employed from the contexts of moral education and mathematics education. Following the model presented in Fig. 1, we discussed how actual studies and educational activities have been conducted at each level in the aforementioned examples.

5.1. Studies at biological and cognitive levels to identify biological mechanisms associated with psychological processes of interest

In Fig. 1, we propose that educational neuroscience research can be examined across multiple levels, including the genetic, evolutionary, neural/physiological, and cognitive/behavioral. Studies at these levels can provide educational researchers and educators with useful insights about the infrastructure of psychological and learning processes involved in educational activities and allow them to develop more effective interventions with empirical evidence. To examine this point, we particularly focused on neuroimaging studies that investigated the neural correlates of psychological processes associated with functionalities that are aimed to be improved in educational settings. Fig. 2 provides a summary of how the upcoming two case studies in moral education and math education incorporate many of the levels proposed in Fig. 1.

First, we shall consider previous neuroscientific studies done in moral psychology that aimed at developing more effective moral educational interventions. Examining the research in morality at the biological level might be particularly informative because morality-related disciplines intend to study morality, which is more susceptible to social desirability bias when traditional research methods (e.g., self-report, survey, interview) are applied [52]. Neuroscientific methods can potentially contribute to the expansion of our knowledge regarding how human morality is functioning with biological evidence by providing us more directly research methods that are less susceptible to the social desirability bias [53–55].

A series of neuroimaging studies that focused on moral functioning provided heuristics to the development of moral educational interventions. First, a meta-analysis of previous fMRI studies of morality identified the common neural correlates of moral functioning [56]. Then, an fMRI study that examined interactions among different brain regions, including those associated with moral motivation and emotion, was conducted with hypotheses that were set based on findings from the meta-analysis [57]. Findings from the fMRI study provided information regarding which psychological processes should be targeted during moral educational interventions, which will be introduced in the next part, and how to design such interventions accordingly [58].

The aforementioned meta-analysis of previous neuroimaging studies was conducted to identity which psychological processes are commonly involved in order to target psychological functioning that will be influenced by educational interventions. Clearly identifying such psychological processes and mechanisms is essential for designing effective interventions [59]. The meta-analysis method enables us to achieve the aforementioned goal thanks to its practical benefits. It is a possible way to overcome the issue of insufficient statistical power that has been a fundamental issue in neuroscience due to small sample sizes, idiosyncrasies in experimental designs [60–62], and possibility of erroneous reverse inference in interpretation [63].

Previous meta-analyses of neuroscience of morality demonstrated common activation foci associated with moral psychological processes [64–67]. In addition, a more recent meta-analysis study was motivated by the Neo-Kohlbergian perspective, a mainstream moral educational theory [68], unlike the previous meta-analyses studies that were conducted from psychological perspectives. These studies reported that brain regions associated with self-related processes, particularly autobiographical self and self-evaluation –the default mode network (DMN) and cortical midline structures (CMS) including the medial prefrontal cortex (MPFC) and posterior cingulate cortex (PCC)– were commonly activated across diverse morality-related task conditions (see Fig. 3).

Based on the findings from meta-analyses, an fMRI experiment was designed and conducted to examine the neural correlates of psychological processes of interest, moral motivation [57]. fMRI experiments can show more specified neural-level processes and mechanisms of interest, which will be targeted during interventions, by employing customized experimental designs, while meta-analyses are only able to show us the neural correlates of such processes and mechanisms in general.

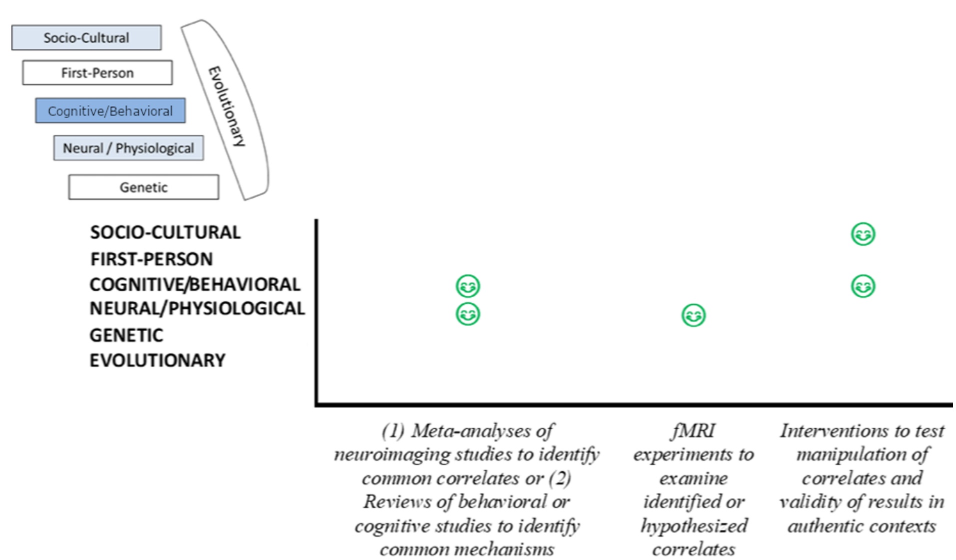

Fig. 2. Application of the different levels of analysis within educational neuroscience in the context of (1) moral education and (2) math education.

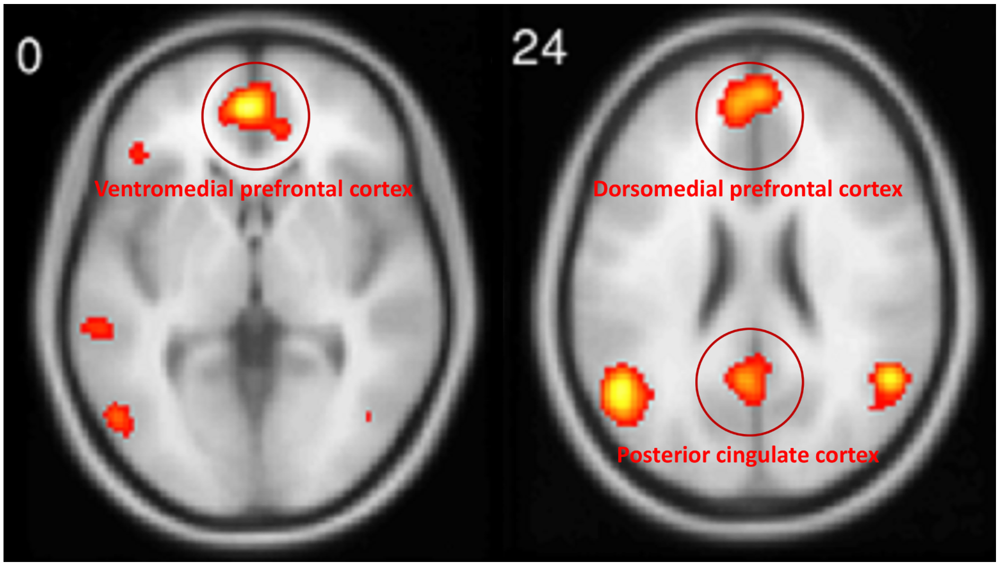

Fig. 3. Common activation foci of moral functioning, including the MPFC and PCC, found by the meta-analysis.

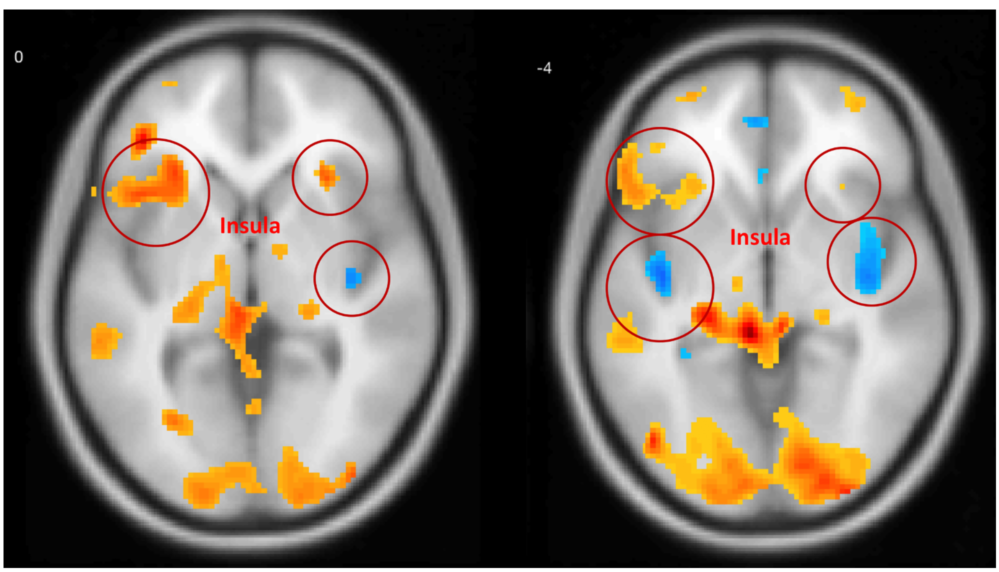

Fig. 4. Brain regions moderated by the MPFC and PCC, including the insula, in moral task conditions. Left: regions moderated by the MPFC. Right: regions moderated by the PCC.

A recent fMRI experiment that was informed by the meta-analysis focused on the possible interaction between moral motivation and self-related psychological processes, which were identified as the common neural correlates of moral functioning in the meta-analysis, within the context of morality-related tasks. In fact, several previous fMRI studies focusing on moral functioning have demonstrated the activation of self-related regions [69,70] in moral task conditions. However, they were mainly interested in identifying activation foci themselves, but not the interaction between self-related psychological processes and moral motivation. The aforementioned recent fMRI study employed more sophisticated analysis methods that allow analysis of interactions among brain regions, such as the psychophysiological interaction analysis [71] and Granger causality analysis methods [72]. This study demonstrated brain regions associated with selfhood, the DMN and CMN, the MPFC and PCC in particular, moderated activity in other brain regions associated with moral emotion and motivation, such as the insula [73], while solving moral dilemmas (see Fig. 4). In short, the fMRI study as well as the meta-analysis demonstrated that self-related psychological processes interacted with processes of moral motivation at the neural level. This result can inform moral educators that moral educational interventions may need to be designed while taking into account the potential influence of self-related psychological processes on moral motivation.[2]

Similarly, examples in math education can also be informative while examining the validity of the multi-level model in educational research. One such intervention in math education that was informed by findings

[2] Of course, the issue of reverse inference can be problematic, if we attempt to associate brain activity in a specific region and a specific psychological process of interest [63]. If we simply connect activity found in the region with the psychological process, then we may neglect the effect of the base rate of activation. To address this issue, we examined the neural correlates of "moral" after controlling for the base rate by utilizing NeuroSynth [108,109]. NeuroSynth performs the control of the base rate by synthesizing brain activity information extracted from the large database of published neuroimaging studies. NeuroSynth demonstrated significant activity in regions that were also found to show significant activity in the cited meta-analysis and fMRI studies [56,57], when the neural correlates of "moral" were analyzed.

in multiple disciplines is a supplemental computerized math software program for students in 2-12 grades called *FASTT Math* (short for **F**luency and **A**utomaticity through **S**ystematic **T**eaching with **T**echnology). This program helps children with math fluency by providing them plenty of practice with retrieval of addition, subtraction, multiplication, and division math facts, thereby developing processing speed and automaticity. *FASTT Math* "begins with a controlled response time of 1.25 seconds, forcing students to abandon inefficient strategies and to retrieve answers from their declarative knowledge network" [63, p. 13]. The design of this intervening program was informed by an extensive body of theoretical and empirical research targeting the development of math fluency. Some of this research will be presented here to exemplify the incorporation of evidence at the cognitive/behavioral, neural, and socio-cultural levels.

Drawing from information-processing theories, *FASTT Math's* five principles guiding instruction are grounded on the cognitive/behavioral level: "(1) determine learner's level of automaticity, (2) build on existing declarative knowledge, (3) instruct on a small set of target facts, (4) use controlled response times, (5) intersperse automatized with targeted nonautomatized facts during instruction'' [64, p. 4]. On a behavioral level, it implies that in order to tackle higher level math content, students must be proficient with the building blocks of math, which often involves quick and accurate retrieval of math facts after some type of number operation [74,75]. This allows students to connect various math facts and concepts, which not only help with retaining learned knowledge but also helps with recalling that knowledge [76,77]. However, becoming proficient in fundamental math knowledge involves establishing connections and combinations between various facts as well as reinforcing them through meaningful practice [78]. Once children develop a functional network that allows them to retrieve math facts, it is important to build automaticity to increase the speed of retrieval through repeated exposure to various retrieval strategies [79]. This method has been shown to be effective not only for typical children but also for children who experience difficulties learning math [76,80,81]. These findings at the cognitive and behavioral levels already make *FASTT Math's* design very purposeful but understanding the mechanisms by which these behavioral changes are possible would lend further credence to the intervention.

FASTT Math's theory of change ties the aforementioned behavioral changes to cognitive mechanisms. By improving the fluency of math fact retrieval through repetitive practice sessions, a person's working memory capacity is free to tackle higher level math. Also, building automaticity also implies more subconscious processing which would make a person less prone to interference from more conscious types of processing mediated by executive function structures, thereby freeing up those resources for higher order processing such as problem solving [82]. These cognitive models are supported by findings in fMRI research that showed the left angular gyrus which is a structure commonly associated with fact retrieval being active not only during a simple fact retrieval task but also during a complex calculation task followed by a short training session. Overall, the comparison between trained and untrained conditions for multiplication problems showed a shift within the parietal lobe from the intraparietal sulcus in untrained problems to the angular gyrus in trained problems [83]. Following the triple-code model [84], the shift of activation within the parietal lobe from the intraparietal sulcus to the left angular gyrus suggests a modification from quantity-based processing to more automatic retrieval; this implies lesser involvement of working memory and real-time calculation. A follow-up fMRI study comparing trained and untrained conditions for multiplication problems showed a shift from frontal activation to more parietal activation implying automaticity and lesser involvement of executive functioning [85].

5.2. Studies at the behavioral, first-person, and socio-cultural levels to design and test interventions in educational settings

Given the proposed multi-level model suggests, research in educational neuroscience requires the involvement of studies from the behavioral to socio-cultural levels, intervention studies in particular, for the improvement of educational outcomes. This would be the case because studies at these levels address issues concerning students' actual experiences within learning contexts and their behavioral and developmental outcomes within real contexts. In this section, we shall focus on how studies at the biological and cognitive/behavioral levels, such as the neuroimaging and physiological studies introduced in the previous section, can inform educational interventions.

Educational intervention studies have improved students' academic achievement and social adjustment in diverse educational settings [86–90]. Thus, such psychological intervention methods can provide useful insights about how to design more effective educational programs. Basically, psychological interventions are designed to tweak psychological processes that are fundamentally associated with a targeted developmental outcome [59]. Hence, it would be necessary to design educational interventions based on findings from psychological experiments successfully identifying which psychological processes are correlated with educational and development outcomes that will be targeted by the interventions.

Similar to the previous section, we continue to introduce examples in moral education and math education in the current section. First, a moral educational intervention study was conducted in the lab and classroom settings [58]; the overall intervention mechanism of this study was established based on findings from the previously introduced neuroimaging studies. This intervention study focused on the utilization of the stories of moral exemplars, who did morally examplary behaviors, for the promotion of students' moral motivation by encouraging them to emulate the presented moral behaviors [91,92]. Although the presentation of moral exemplars can promote motivation to engage in moral behavior through vicarious social learning [93], moral elevation [94,95], and upward social comparison [96,97], the mere presentation of moral exemplars can backfire when social and moral psychological mechanisms are not carefully considered. Particularly, when extreme moral exemplars, such as historic moral figures (e.g., Mother Teresa) that have usually been introduced in moral education textbooks are presented, students might feel negative emotional responses, such as extreme envy and resentment, and tend not to emulate presented moral behaviors, due to the activation of the self-defense mechanism [98–101].

The aforementioned intervention study attempted to address this issue by examining effects of different types of exemplars with an intervention design based on the neuroimaging findings. The neuroimaging studies demonstrated significant interactions between self-related processes and moral motivational processes and the role of self-related processes in moral functioning at the neural level [56,57]. Based on these findings, the intervention study focused on the connectivity between students' selfhood and presented exemplars. The study examined whether attainable and relevant exemplars, such as family members, friends, and close-other exemplars, that might be perceived to be closer to students' selfhood more effectively promoted moral motivation compared with distant exemplars, such as historic figures. Accordingly, two experiments, one in a lab and the other in a classroom, were conducted.

The lab experiment compared influences of attainable versus unattainable exemplary stories on voluntary service engagement as a proxy for moral motivation [58]. In this experiment, a total of 54 college students participated and their voluntary service engagement was measured before and eight weeks after the intervention session. They were randomly assigned to one of these three groups: attainable, unattainable, and control groups. Attainable group members were presented with the stories of youth exemplars who participated in a

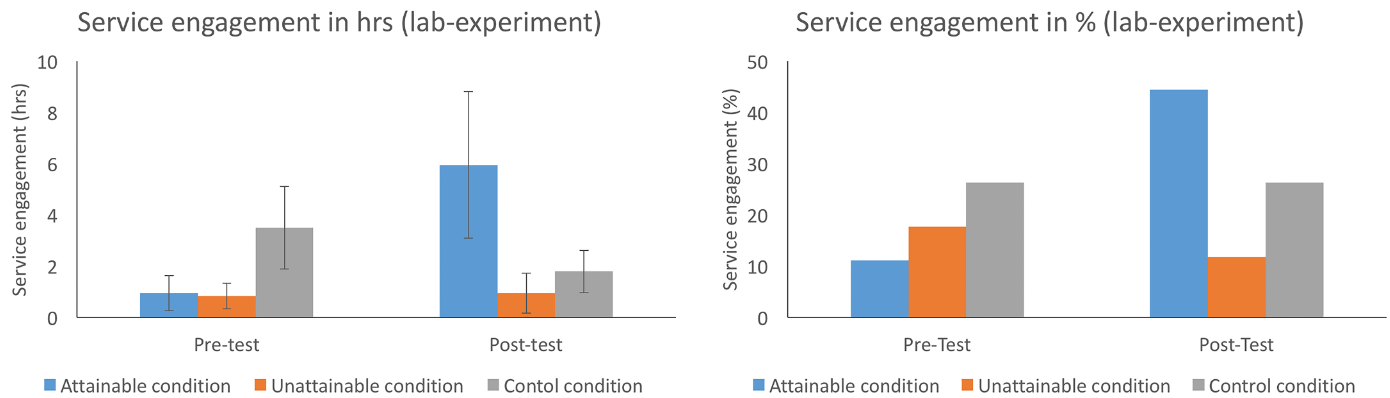

Fig. 5. Changes in engagement rate in each condition in the lab experiment. Left: engagement rate quantified in hours. Right: engagement rate quantified in percentage.

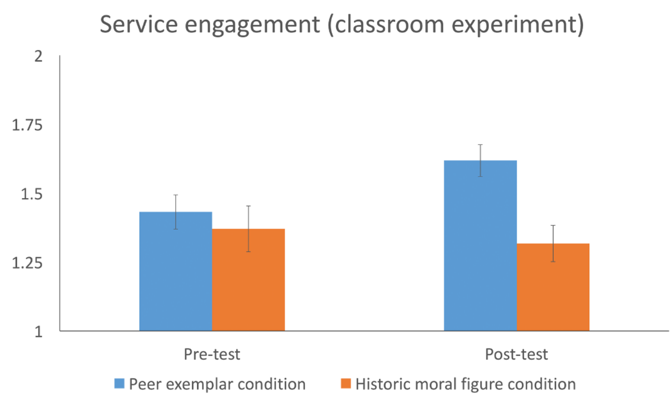

Fig. 6. Changes in service engagement in each condition in the classroom experiment.

reasonable amount of service activities (≤ 2 hours per week). On the other hand, participants in the unattainable group were presented with the exemplary stories of extreme service engagement (≥ 10 hours per week). The control group was presented with non-moral stories, such as general sports news reports. Findings demonstrated that the attainable group showed significantly greater increase in the service engagement compared to other groups (see Fig. 5).

In addition, a classroom intervention experiment tested the same effect in an educational setting among 107 8th graders to examine the ecological validity of the lab-tested intervention method [58]. The participants were assigned to one of these two groups: peer exemplar and historic figure groups. On the one hand, the peer exemplar group was asked to present and discuss moral virtues and behaviors done by peer exemplars, such as friends, teachers, and family members, that perceived to be close to themselves. On the other hand, participants assigned to the historic figure group were requested to talk about moral virtues and behaviors of historic moral exemplars, such as Martin Luther King, that seemed to be distant from themselves. Interventions were conducted for once a week for an hour for eight weeks. Participants' service engagement was measured before the beginning of the intervention period and twelve weeks after the pre-test survey. The results demonstrated that the positive change in service engagement in the peer exemplar group was significantly greater compared to the historic figure group (see Fig. 6). In short, these intervention experiments, which were informed by the studies at the neural and cognitive levels and focused on the behavioral to first-person levels, successfully tested which types of exemplars can more effectively promote moral motivation in realistic educational settings.

Second, we shall review a relevant example in math education. In addition to being grounded in the aforementioned behavioral, cognitive, and neural levels, *FASTT Math* has also been shown to be a successful intervention in authentic contexts thereby also grounding it on the socio-cultural level. Using a Pre-test/Intervention/Post-test design, 160 children with disabilities of ages 7-14 were equally distributed into a treatment group or a control group. The treatment group received the *FASTT Math* intervention averaging 10 minutes daily in addition to their classroom math instruction while the control group only received their typical classroom math instruction. A comparison group of typically developing children were also included. The treatment group showed a 73% increase in math fact retrieval (45 additional facts) in the post-test compared to the pre-test. But the control group showed no change in their fact retrieval ability, and the typically developing group showed a non-significant increase of 8 additional facts during the post-test. This attests to the practicality and utility of the intervention for learning in authentic contexts [102].

6. Conclusions

As an emerging transdisciplinary area of research, educational neuroscience is facing challenges in formulating theoretical frameworks that can link and integrate perspectives, findings, and research methods from neuroscience, education, and other mediating disciplines. Here we first proposed a theoretical framework that integrated levels of analysis from various fields including education and neuroscience; then we discussed how educational neuroscience can examine learning and cognition across these levels, and provide new insights that could not be possible without crossing or integrating these levels. In the second part of the paper we presented a research program in moral psychology and ethics education as well as an intervention in math education as case studies for how educational neuroscience research can integrate findings and methods across multiple levels to address a set of shared, core research questions. We argue that educational neuroscience differs from cognitive neuroscience in that it concerns how learning takes places in authentic educational contexts by drawing on findings from multiple disciplines; in addition to understanding the mechanisms of learning, it also strives to develop interventions and find evidence-based solutions to educational problems. This requires development of research methodologies that can allow the study of learning and cognition with authentic tasks and in authentic contexts. When methodologies from various fields are integrated, this convergence can counter challenges by operating quickly and generating frequent data points to inform large-scale practice and policy decisions.

In addition, for large-scale implementations of developed educational interventions within wider contexts, we may need to consider employing modeling and computer simulations as well. Given that the implementations of interventions produce long-term, large-scale outcomes in students' developmental trajectories [86,103], it is necessary to carefully predict such outcomes before the implementations. In this process, mathematical modeling and computer simulations based on up-to-date scientific computation methods would enable us to predict long-term, large-scale outcomes of interventions with data collected from lab-level or classroom-level studies, such as those introduced in this paper. We can utilize computational techniques to model complex structures of a phenomenon based on small-scale empirical data , which can than be used to predict outcomes of large-scale implementations [104]. Recent studies have demonstrated that such predictive models and simulations can be implemented with evolutionary modeling and deep learning techniques [105–107]. Once data on small-scale intervention outcomes are collected, it is possible to model and simulate outcomes of longer and larger-scale interventions with the aforementioned techniques. Previous studies have shown that the accuracy of predictions made with the new computational methods is significantly higher than those made with traditional regression methods [105].

We shall conclude that future efforts in educational neuroscience should address the challenge of developing theoretical tools and research methods that integrate different levels of analysis that traditionally exist solely in education, neuroscience, or other siloed domains. And as these tools and methods gain momentum, there may also be a need for a shift to change the name of the field from *educational neuroscience* to a more inclusive term that truly depicts the transdisciplinary nature of the field and its integrative power to transform the landscape of learning.

Conflict of interest

The authors certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Ethical statement

Hereby, I, Hyemin Han, consciously assure that for the manuscript, Connecting Levels of Analysis in Educational Neuroscience: A Review of Multi-level Structure of Educational Neuroscience with Concrete Examples, the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
2) The paper is not currently being considered for publication elsewhere.
3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
5) The results are appropriately placed in the context of prior and existing research.
6) All sources used are properly disclosed (correct citation). Literally copying of text must be indicated as such by using quotation marks and giving proper reference.
7) All authors have been personally and actively involved in substantial work leading to the paper, and will take public responsibility for its content.

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