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 perspective 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 moral education.

Keywords: educational neuroscience; multi-level theoretical framework; neuroimaging; meta-analysis; educational intervention; computer simulation

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 early 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 a research project on development of moral decision making, which involves a series of studies each targeting a different set of levels of analysis, from classroom interventions to functional magnetic resonance imaging (fMRI) 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 teaching in this domain. Our expectation is that the framework and the case study presented here will help with responding to concerns about viability of educational neuroscience as a field.

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 discussion 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 practice in education (e.g., reading, numerical cognition). 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 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. In this approach neuroscience findings can only be meaningful for education if it goes through an interpretive filter that is 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 criticisms. For example Bowers [3,4] argued that it is psychological science that provides a scientific grounding for education, and neuroscience rarely provides insights into learning and teaching outside of psychology. In addition, he 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 development of non-impaired compensatory skills.

In his response to the criticisms by Bowers, 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 on 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 integrates 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 level of sociocultural, phenomenological, and cognitive explanations. In its journey from the 1950s cognitivist era to the 21st century, educational research has moved from more reductionist, post-positivist theories to post-structuralist, situated, and constructivist frameworks. 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 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 in educational research [13] are re-instantiated with educational neuroscience. Part of the educational research and practice 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 does not only retain the levels of explanation that are deployed in neuroscience, but also finds ways of incorporating the levels of explanation that is established in education. Apart from theoretical differences and differences in philosophical assumptions about the nature of learning in different traditions, there is also a methodological divide between neuroscience and education. Educational neuroscience, being the synthesis of these two fields, 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 a research program on moral psychology and education, involving multiple studies spanning across the different levels of analysis presented.

Educational neuroscience is often characterized as a bridge between neuroscience and education [14]. This metaphor implies that educational neuroscience is a space where researchers and practitioners from two fields interact, but not a field with its own vision, community of researchers, big questions, theoretical frameworks, and methodologies. Alternatively, educational neuroscience can be characterized as a new field that fills the gap between brain sciences and education [15]. This metaphor implies a burgeoning, transdisciplinary field, in close contact with other relevant fields, but with its own big questions, theories, methodologies and community of researchers. In its current state, the bridge metaphor is a better characterization of educational neuroscience. However, the fast-paced progression of the field poses a future vision that better matches the “filling the gap” metaphor. However, before this can happen, big questions for the field, theoretical paradigms, and methodologies need to emerge.

There are two main characteristics of educational neuroscience that distinguish it from other fields within brain science. 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 educational and brain science research. The main goal should not be 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 more comprehensive, 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 inform educational practice and policy. One difficulty here is the lack of a shared lingua across people from different fields and paradigms. There is a need for a theoretical framework that is operationalized across all these levels that can act as the basis that can bring together these levels.

Multiple Levels & Diverse Methodologies in Educational Neuroscience

After Marr’s influential work on distinct levels of analysis for information processing systems [16], it became common to approach cognition as a complex system that has multiples levels of organization [17]. Marr introduced three levels, computational, algorithmic, and implementation. The computational level describes the processes and operations conducted by the system, and sub-tasks involved in each. However, it does not describe how the system does these operations. 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 involves the physical mechanism where the computation is performed, whether it is biological, silicon-based, or any other form of hardware.

Given that approaching cognition as a computational phenomenon became ubiquitous starting with the cognitive revolution in the 1950s, Marr's levels of analysis for information processing systems in general, highly impacted our approach to cognition. However, the human cognitive system hardly presents 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 likewise we don't need to understand the implementation level to make sense of algorithms. While the argument for independence neatly applies to computational systems (i.e., the same algorithm can run on many different forms of hardware), its application to human cognition and neuroscience is problematic. Churchland and Sejnowski [18] 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 [18] proposed a model for structural levels of organization in the nervous system (from micro to macro scale), which involves molecules, synapses, neurons, networks, maps, systems, and the central nervous system. They 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 cognition. In addition, educational neuroscience focuses on how we should design learning environments based on what we know about human cognition. We argue that approaching cognition as a complex system that should be studied in distinct but interrelated levels is applicable to educational neuroscience as well. However, given the applied and contextual nature of educational neuroscience, we propose alternative levels of analysis that captures both biological and socio-cultural aspects of educational neuroscience. Filling the gap between education and brain sciences, educational neuroscience concerns levels of explanation and inquiry from both domains. In Fig. 1, a characterization of these levels – from socio-cultural to genetic – is presented. Each level of explanation feeds from a different set of fields. For example, socio-cultural theories of learning abound in education, whereas neural and cognitive-level explanations are inherent to cognitive neuroscience. Here we present a short description of each level, proposed as part of the multi-level framework.

Socio-cultural level

At the sociocultural level, learning is defined as a situated activity taking place in a socio-cultural context [19]. At this level, research on learning is conducted using design-based research [20], and a wide range of other qualitative methodologies. According to situated theories, learning occurs as a result of situated activity in authentic contexts. This is the most ecologically valid level of inquiry.

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 commonly ignored 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 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]).

Behavioral level

Behavioral studies focus on measuring learning and studying cognitive processes through 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.

Cognitive level

Cognitive level involves study of mental processes (e.g., memory, attention, perception). An important focus at this level is developing mathematical / computational models of cognition and learning. Based on an information processing approach [24], cognition is characterized as processing inputs (perception) to produce outputs (action), instead of simply responding to stimuli (behaviorism). Cognitivism distinguishes between perception and action, as well as emotion and cognition. The cognitivist paradigm is strong in psychology and most cognitive neuroscience research target unfolding the neural correlates of the processes at the cognitive level.

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 are pioneering psychological and brain sciences [25]. 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)). One shortcoming is the lack of ecological validity of most studies conducted at the neural level. Because there are a wide range of constraints limiting the tasks participants can engage with, cognitive neuroscience investigations often can’t use authentic tasks or take place in authentic environments. This is currently a major challenge for educational neuroscience. However there is a growing body of literature reporting results and new methods that aim at conducting 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. They are often used in psychology and, especially in affective and social neuroscience studies. Physiological measures are promising in studying student motivation and affect during learning in authentic contexts.

Evolutionary level

Evolutionary explanations for human cognitive abilities often help make connections among different cognitive faculties that would not be obvious otherwise. Studies at this level either concern research on anthropological evidence on how human cognitive abilities evolved or comparative studies with non-human animals. Evolutionary psychology is an important subfield of psychology and comparative neuroscience studies with non-human animals, particularly primates, support inferences about the evolution of human brain and cognition.

Genetic level

Genetic level concerns how genetic markers interact with learning abilities 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 [28].

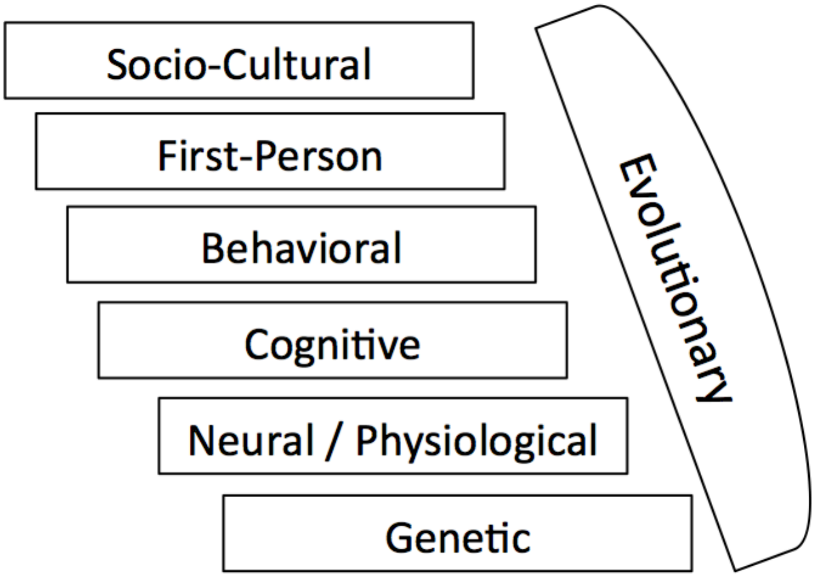

Figure 1. Levels of analysis for educational neuroscience.

Challenges

Authentic tasks

Most of the tasks students are engaged in in the classroom are highly complex compared to the tasks traditionally used in experimental research. This makes traditional experimental paradigms unsuitable for studying authentic learning processes in the classroom. Experimental research requires averaging of data (both behavioral and neural) collected across many trials. Experimental research also controls for the sequencing of trials from different conditions to control for priming effects. Both averaging of many trials of data across conditions and controlling for priming effects are difficult to do when studying an authentic task (both in the lab and in the classroom). In authentic tasks the sequencing of events can be a dependent factor. The learners might follow different trajectories during a task. These trajectories might be informed by individual differences and can be a valuable source of data. Nevertheless, the more complex and uncontrollable nature of authentic tasks makes averaging and controlling for confounds difficult.

Authentic contexts

The major shortcoming of experimental lab studies for education 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 [29] and fNIRS [30] studies were conducted in not strictly controlled classroom contexts.

Relating levels

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” [16]. 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.

Research Design

Currently research that targets combining neuroscience and education approaches generally is 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 [31]. 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. Here we review various research design approaches that incorporate perspectives, paradigms and research methodology from education and neuroscience. These methodologies represent various degrees of integration between the two fields, some of them tilting towards neuroscience, others towards education, and some representing a further form of integration. The methodological approaches listed below are not mutually exclusive and most studies employ more than one of these approaches.

Types of Research Design

Pre-test, intervention, post-test. This form of design allows for using authentic tasks in the intervention stage with only behavioral data collection, and using more traditional neuroimaging methods during the pre/post-test stages. The data analysis focuses on changes from the pre-test to post-test period as a result of the intervention. The intervention can be an authentic task in the lab or a classroom activity.

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., 30][29]. 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.

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 [32,33] neuroimaging studies often do not use authentic tasks. One exception to this is neuroimaging research on video games [26] 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 [26,34].

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 [35]. 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. 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 [36]. 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. [37–39]. There are also some efforts in using participants' reported first-person experience as a guide, while analyzing behavioral and neural data [23,40]. 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 the current state of things 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.

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 in the reality, we review previous studies that have attempted to connect the different levels and methodologies. In particular, we focus on a case in the field of moral education as a concrete example. The reviewed studies include previous meta-analyses and fMRI studies related to moral functioning, intervention studies inspired by the findings from the aforementioned neuroimaging studies, and computer simulations to model policy-level activities based on small-scale findings. We review these studies in order to exemplify how the multi-level approach can be implemented in educational neuroscience.

Utilizing Neuroscientific Methods in Educational Contexts

In this section, we reviewed how the proposed conceptual framework for educational neuroscience can be implemented with a concrete example in moral education. We decided to delve into the case of moral education, because the application of neuroscientific methods would be particularly beneficial for moral education among various fields in education. Because studies in moral psychology and moral education have focused on one of the most philosophically and conceptually sophisticated nature of human psychology, that is, morality, it would be significantly more susceptible to social desirability bias compared to other domains of human psychology. For instance, people might pretend to become a morally better person when they are participating in survey or observation studies examining moral development. As a result, moral psychologists and educators have tried to develop more sophisticated surveys and tests to minimize the possibility of such social desirability bias [41]. Given this, 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 [42–44]. In order to see how neuroscientific studies can contribute to moral education in practice, as the first step in this process, we consider two specific methods, i.e., meta-analysis and fMRI methods, which can illuminate psychological processes involved in moral functioning, as components in the research program of educational neuroscience.

First, a meta-analysis of previous neuroimaging studies can identify 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 [45]. A meta-analysis of neuroimaging studies is a feasible option for identifying such psychological processes while also providing us with a direct and statistically-valid way to examine internal neural-level psychological processes. A meta-analysis can also address several issues associated with traditional neuroimaging methods, such as the lack of statistical power originating from relatively small sample sizes, idiosyncrasies in experimental designs [46–48] and possibility of erroneous reverse inference in interpretation [49]. In case of the present example of moral education, a meta-analysis of previously conducted neuroimaging studies can identify common activation foci of interest in moral functioning. For the meta-analysis of previous neuroimaging studies, the activation likelihood estimation (ALE) implemented by *Ginger ALE* is one of the most valid and feasible analysis methods [50,51]. While systematic or qualitative review methods are also possible in a meta-analysis, ALE is a quantitative method that provides us with empirical evidence pertaining to psychological processes of interest with statistical validity.

Previous meta-analyses of neuroimaging studies focusing on moral functioning using *Ginger ALE* have demonstrated common activation foci associated with moral psychological processes [52–55]. However, the research questions and hypotheses of these meta-analyses were not based on theories of moral development and moral education, so their developmental, psychological, and educational implications for educational neuroscientific studies are limited. A recent meta-analysis, however, designed its analytic framework and hypotheses [56] based on the Neo-Kohlbergian perspective, a mainstream moral psychological theory that has been applied in moral educational programs in diverse domains, such as professional ethics programs [57,58]. This study 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 Figure 2). Given these results, selfhood might be commonly engaged in moral functioning. fMRI and intervention experiments can be guided by these findings; they may focus on self-related psychological processes while setting their research questions and experimental designs.

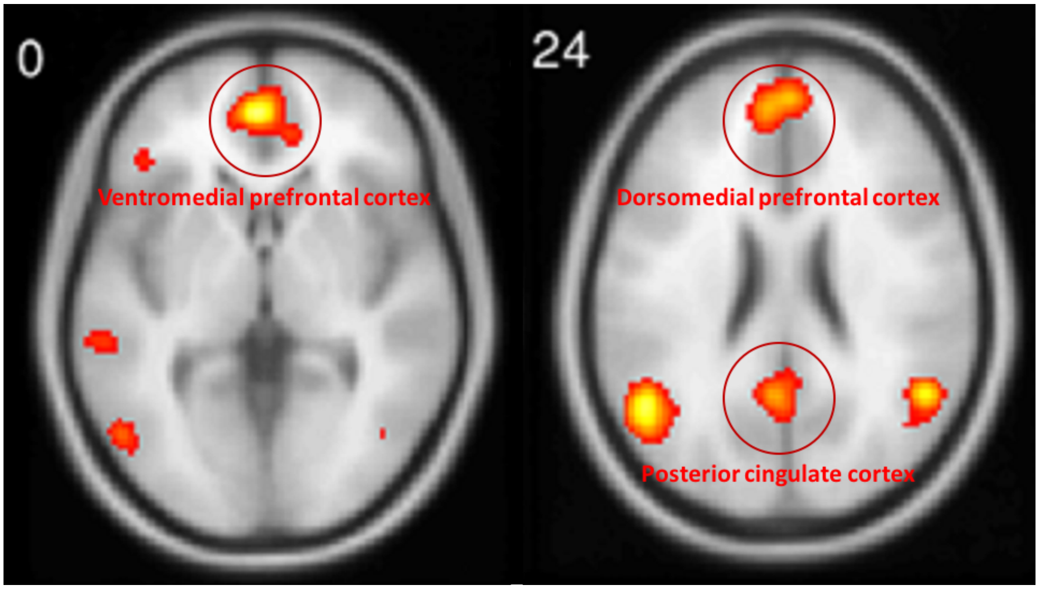

Figure 2. Common activation foci of moral functioning, including the MPFC and PCC, found by the meta-analysis.

Second, we can conduct an fMRI experiment that is designed to examine the neural correlates of psychological processes of interest, e.g., moral motivation, based on the findings from meta-analyses. Such an fMRI experiment can show us more specified neural-level processes and mechanisms of interest by employing customized experimental designs, while meta-analyses are only able to show us the neural correlates of such processes and mechanisms in general. In the case of moral psychology, previous fMRI experiments have demonstrated the neural correlates of moral functioning by employing diverse experimental paradigms [59,60]. These studies have shown that various brain regions associated with cognitive [61,62], affective [63–65], motivational [66,67], and self-related processes [60,68] were activated in moral task conditions.

Particularly informative is a recent fMRI experiment with a set of hypotheses based on findings from the previous meta-analysis that showed significance of self-related processes in moral functioning [69]. Although several previous fMRI studies have demonstrated the activation of self-related regions [60,68], they were mainly interested in identifying activation foci themselves, but not how self-related psychological processes moderated moral functioning at the neural level. Instead, the recently conducted fMRI experiment investigated how brain regions associated with selfhood, the DMN and CMN, moderated activity in other brain regions associated with moral emotion and motivation, such as the insula, while solving moral problems by utilizing the psychophysiological interaction analysis [70] and Granger causality analysis methods [71]. Figure 3 demonstrates the results of these analyses. As hypothesized, the analysis indicated that neural activity in regions associated with selfhood in the DMN and CMS, particularly the MPFC and PCC, significantly moderated activity in moral emotion and moral motivation-related regions, as well as the insula which has been known to assist brain regions in the generation of appropriate behavioral responses to salient stimuli [72]. Consequently, this fMRI experiment was able to support hypotheses based upon previously published neuroimaging studies of morality and their meta-analyses, and identify psychological processes that will be targeted by intervention experiments, i.e., self-related psychological processes.

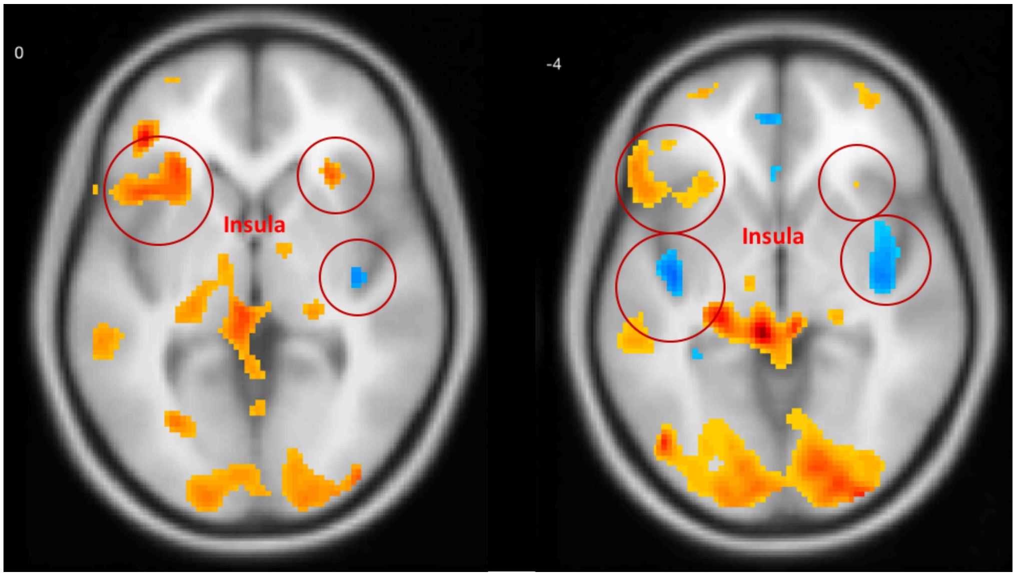

Figure 3. Brain regions moderated by the MPFC and PCC, including the insula, in moral task conditions. Left: regions moderated by the MPFC. Right: regions moderated by the PCC.

Psychological Intervention Methods Founded by Neuroscientific Studies

Before applying findings from the neuroimaging studies to moral education in practice, we have to test whether the prototype of educational programs targeting the psychological processes are identified by neuroimaging studies. It can be tested by conducting relatively small-scale psychological intervention experiments. Such intervention experiments can be an interface between neuroscience and education in practice by providing evidence for a certain intervention that is designed based on findings from neuroscientific studies. As a concrete example in the field of moral education, educational interventions utilizing the stories of moral exemplars are considered hereafter.

Interventions based on psychology, particularly social and educational psychology, have improved students' academic achievement and social adjustment in diverse educational settings [73–77]. Thus, such psychological intervention methods can provide useful insights about how to design more effective moral education programs. Basically, psychological interventions are designed to tweak psychological processes that are fundamentally associated with a targeted developmental outcome [45]. 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.

In traditional moral education, the stories of moral exemplars have been widely utilized in educational settings. Moral educators and parents have presented the stories of moral exemplars, who did morally great behaviors, in order to promote children's moral motivation by encouraging them to emulate the presented moral behaviors [78,79]. The presentation of moral exemplars can promote motivation to engage in moral behavior through vicarious social learning [80], moral elevation [81,82], and upward social comparison [83,84]. However, 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 [85,86]. During the presentation of such extreme exemplars, students might think that the presented moral behaviors are not emulatable given their ability, and might activate the self-defense mechanism protecting their selfhood by isolating them from moral values to deal with the negative emotional responses [85,87,88]. Thus, it is necessary to carefully examine psychological processes associated with interventions in order to make the interventions more effective while minimizing possible negative outcomes.

As a concrete example, we reviewed an intervention study consisting of two moral educational intervention experiments. These two psychological intervention experiments used the stories of moral exemplars and tested which type of exemplary stories better promoted motivation to engage in moral activity [89]. In order to determine which psychological processes were targeted and tweaked during intervention experiments, findings from aforementioned neuroimaging studies, a meta-analysis and fMRI study, were reviewed. These neuroimaging studies have demonstrated that brain regions associated with self-related psychological processes, particularly autobiographical memory processing, were commonly involved in moral functioning in general [56], and moderated moral emotion and motivation [69]. Given such findings from the previous neuroimaging experiments, intervention experiments manipulated the perceived distance between presented moral exemplars and participants' self-concept.

Two intervention experiments, one lab experiment and one classroom experiment, that were founded by the neuroimaging studies were conducted. The experiments presented two different types of exemplary stories: attainable and unattainable moral stories. Given the significant positive interaction between self-related and moral functioning-related brain regions, as the presented moral stories are perceived to be closely associated with participants' self-concept, the motivating effect of the stories would become greater [90]; attainable stories (e.g., stories of peer exemplars) would more strongly promote motivation compared to unattainable stories (e.g., stories of historic figures), which seem distant from participants. In fact, previous social psychological intervention experiments focusing on non-moral motivation also reported that attainable stories better promoted motivation while unattainable stories might backfire [91,92].

A lab experiment was conducted to examine the motivating effects of different types of moral stories among college students; it used engagement in voluntary service activities as a proxy for moral motivation [89]. A total of 54 college students participated in this experiment. Their pre- and post-test voluntary service engagement were measured. The participants were randomly assigned to one of these three groups: attainable, unattainable, and control groups. On the one hand, attainable group members were presented with the stories of youth exemplars who participated in a 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. After presenting attainable or unattainable moral stories to the participants, their post-test voluntary service engagement was surveyed once again eight week later to examine change in engagement. Findings demonstrated that participants assigned to the attainable group showed significantly greater increase in the service engagement compared to other groups (see Figure 4).

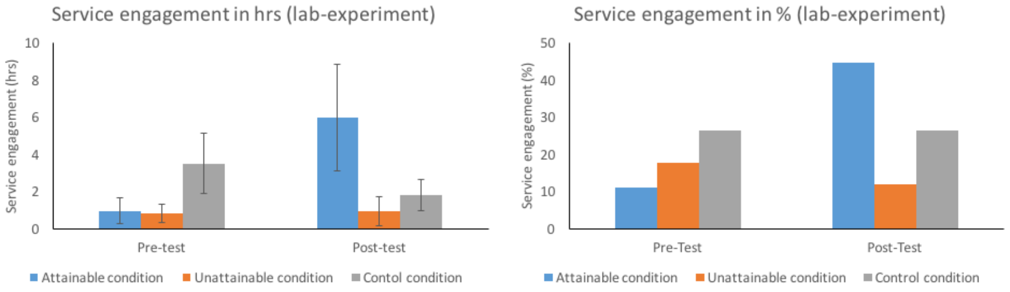

Figure 4. Changes in engagement rate in each condition in the lab experiment. Left: engagement rate quantified in hours. Right: engagement rate quantified in percentage.

In addition, a classroom intervention experiment tested the same hypothesis among

107 8th graders [89]. This classroom-level experiment was performed to apply the lab-level intervention to more realistic educational settings. Similar to the previous lab experiment, 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 deemed to be attainable. 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 Mother Teresa and Martin Luther King, that seemed to be extraordinary and unattainable to them. Interventions were conducted for once a week for an hour during eight weeks. Participants' service engagement was measured before the beginning of the intervention period and twelve weeks after the pre-test survey. Participants' answers were quantified on a one to five scale ("1. None"— "5. More than once per week"). Survey results demonstrated that the positive change in service engagement in the peer exemplar group was significantly greater compared to the historic figure group (see Figure 5).

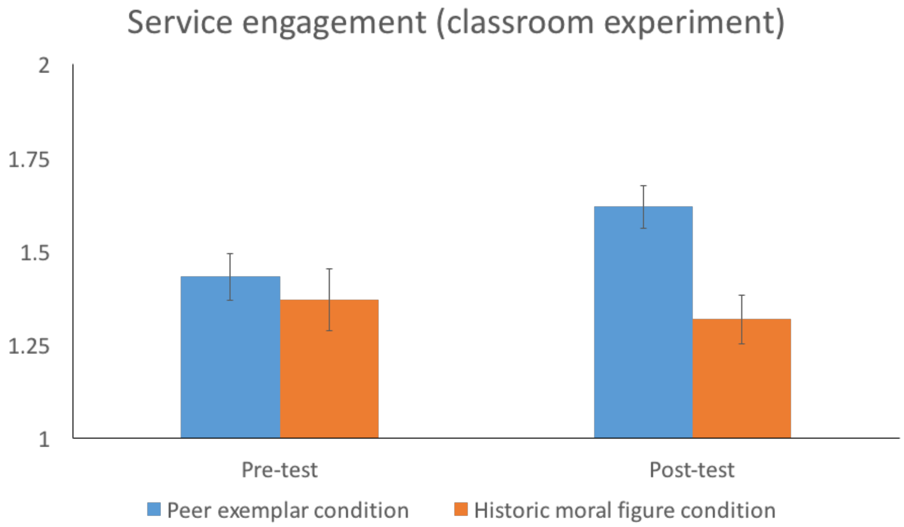

Figure 5. Changes in service engagement in each condition in the classroom

experiment.

The findings from these two experiments supported the hypothesis that was founded by the previous neuroimaging studies. Attainable exemplars better promoted moral motivation compared to unattainable exemplars. These findings are coherent with the neuroimaging experiments that showed the moderating effect of self-related psychological processes on moral emotion and moral motivation. Consequently, we shall conclude that our conceptual framework pertaining to how to utilize neuroscience in educational practice has been supported by the presented example case, moral educational interventions based on neuroimaging studies of moral functioning.

Applying Evolutionary Modeling and Computer Simulation to Inform Educators and Policy Makers

Although we have demonstrated that it would be possible to design more effective educational interventions based on findings from neuroimaging studies, how to apply such educational interventions at the large scale, such as at the school or district level, is still unclear. Because findings from the aforementioned intervention experiments, lab and classroom experiments, might only be valid at a relatively small scale (lab or classroom level), these findings cannot be generalized without any further investigations. Because even a brief educational intervention might produce long-term developmental outcomes among students [73,93], we should carefully consider how to properly predict long-term, large-scale outcomes of interventions based on available evidence, such as, evidence from relatively small-scale intervention experiments. However, due to the lack of time and resource, it is difficult to conduct multiple long-term, large-scale experiments in real educational settings to examine such outcomes in reality [94,95].

Computer simulation methods can address this limitation by enabling researchers and educators to perform these predictions accurately, and thereby, provide basic information regarding how to scale-up designed interventions. Particularly, simulation methods based on evolutionary modeling [96] and deep learning [97] might be feasible methodologies to conduct such predictions. As a part of the conceptual framework of educational neuroscience, these methodologies could also be included because even though they originated from parallel fields such as evolutionary biology, artificial intelligence, and artificial neural network modeling, they can contribute to interfacing neuroscience, education, and all other mediating disciplines in practice.

First, evolutionary modeling using the Evolutionary Causal Matrices (ECM) can predict the future status of a certain system consisting of different types of individuals [98]. The ECM predict the future status at t_0+n from the status change between t_0 and t_0+1 with iterative calculations; with n iterations, the predicted status at t_0+n can be calculated [96]. In the case of the moral educational intervention, we can set the t_0 status as the pre-test voluntary service engagement and t_0+1 as the post-test engagement. By performing iterative calculations, we can compare the effectiveness of interventions according to their types and application frequencies. Due to the limitations of time and resource in educational intervention research, the majority of simulations might be performed for relatively short-term predictions; however, the theoretical framework of the simulation method can be applied in relatively long-term longitudinal predictions as well.

For this simulation, findings from the aforementioned intervention experiments are revisited. In order to predict developmental outcomes of the moral exemplar-applied interventions, ECM were created using pre- and post-test service engagement data, and iterative simulation processes were performed with the created ECM [99,100]. As presented in Table 1, ECM for simulations were created by comparing the ratio of participants who engaged in service activities at the pre- and post-test periods in each experimental condition. They demonstrate the transitions between statuses (engaging vs. not engaging) across two timepoints; for instance, participants were more likely to start or continue to engage in service activities in the attainable condition compared to the unattainable condition. Based on these ECM, long-term outcomes of the interventions were simulated through iterative learning processes with different intervention types and frequencies. As presented in Figure 6, the attainable exemplar-applied intervention can better promote engagement. Its effect size declines as the frequency of application gets lower (see Figure 7). Thus, the intervention should be performed at least once per every 10.5 months to produce a large effect. We remark that the ECM-based prediction is useful at predicting future outcome sequences based on a simple stochastic model with a relatively small number of estimated parameters.

		Engaging (*t*)	Not engaging (*t*)
Attainable condition	Engaging (*t*+1)	.90 (ECM [1,1,1])	.44 (ECM [1,1,2])
	Not engaging (*t*+1)	.10 (ECM [1,2,1])	.56 (ECM [1,2,2])
Unattainable condition	Engaging (*t*+1)	.64 (ECM [2,1,1])	.12 (ECM [2,1,2])
	Not engaging (*t*+1)	.36 (ECM [2,2,1])	.88 (ECM [2,2,2])
Without any intervention (control condition)	Engaging (*t*+1)	.71 (ECM [3,1,1])	.28 (ECM [3,1,2])
	Not engaging (*t*+1)	.29 (ECM [3,2,1])	.72 (ECM [3,2,2])

Table 1. Created ECM for different types of interventions

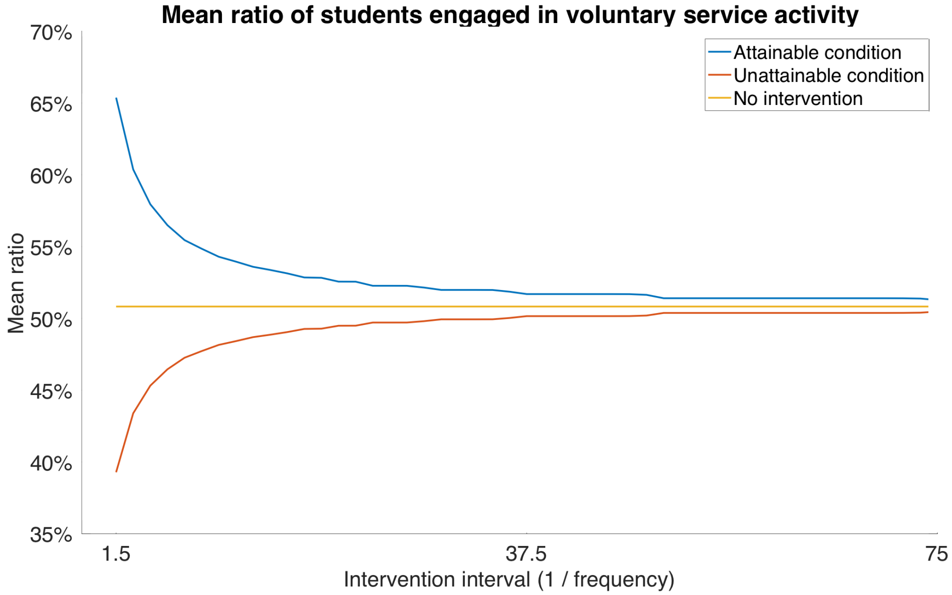

Figure 6. Change in the mean ratio of engagement with different intervention frequencies across different conditions.

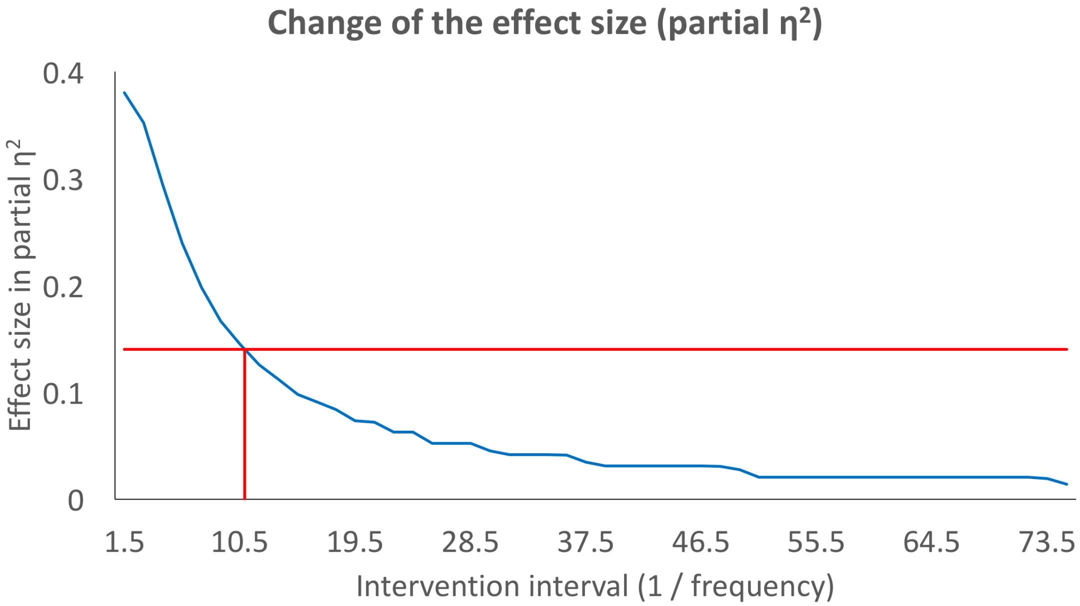

Figure 7. The estimate effect size of the attainable exemplar-applied intervention per different intervention frequency. The red line indicates a threshold for a large effect size (partial $\eta^2 = .14$, see [101]).

When a large enough amount of training data is on hand, one can apply machine learning algorithms in order to develop a data-driven prediction model. Furthermore, we might have to employ the machine learning method when multiple covariates, such as demographical variables, are required to be considered, because the ECM only allow us to predict outcomes solely based on one independent variable. Among various machine learning algorithms, artificial neural networks with many layers, or simply "deep learning", is currently the most popular due to its outstanding performance in many classical applications such as image classification, object recognition, speech recognition, etc. The deep architecture of deep learning corresponds to a hierarchy of features, factors, or concepts, where higher-level concepts are defined from lower-level ones, and the same lower-level concepts can help define many higher-level concepts (Deng & Yu, 2014, p. 200).

In our example, the deep learning method was applied to the moral education intervention data. Using Google's TensorFlow [102], a two-layered convolutional network, for predicting intervention outcomes, was trained (see Figure 8) [103]. The prediction network takes pre-test variables (i.e., service engagement, gender, intervention type, emotional responses to intervention activity, intention to engage in service) as inputs, and predicts the post-test outcome (i.e., whether or not to engage in service at the post-test). An iterative training algorithm (called the stochastic gradient method) was used during simulation. Findings reported that the prediction performance was maximized after about 4,000 iterations of the training algorithm.[1] The best prediction model with the

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[1] Note that the prediction performance decreases after a certain number of

convolutional network clearly outperformed simple logistic regression: while the accuracy of logistic regression was 75.47%, that of the best convolutional network reached 85.16% (see Table 2). Given these results, the deep learning method can enable researchers, educators, and policy makers to simulate and prototype large-scale intervention experiments or applications, particularly when multiple independent variables and covariates should be considered in a prediction.

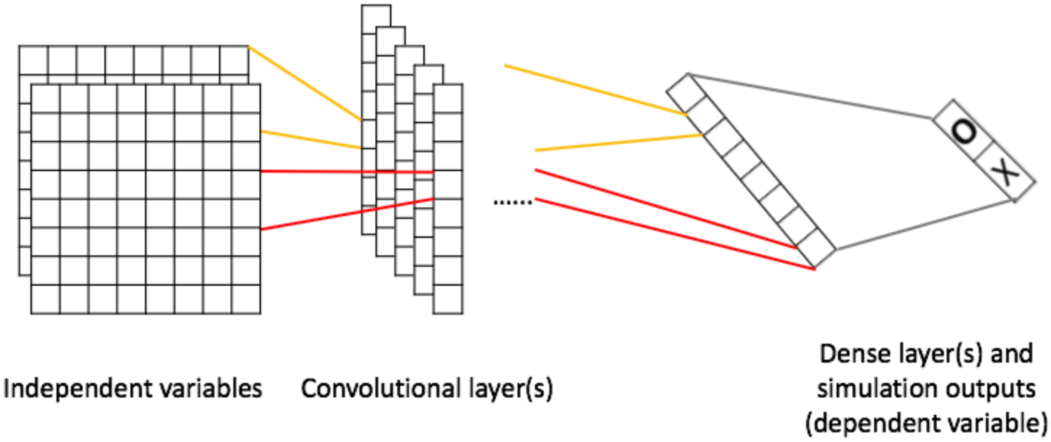

Figure 8. Illustrative example of a deep learning neural network

Iteration #	TensorFlow simulation accuracy (%)	Logistic regression accuracy (%)
500	79.82%	75.47%
1000	82.62%	
2000	83.83%	
4000	85.16%	

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iterations. This is called overfitting, which happens when a prediction model starts capturing in the model noise of the data, losing predictability.

8000	70.30%

Table 2. Accuracy of TensorFlow simulation across different iterative learning conditions. Colored cells indicate the best accuracy outcome.

Aforementioned computational methodologies, the ECM and deep learning, might be feasible and accurate ways to predict long-term, large-scale outcomes of educational interventions based on relatively small-scale data, e.g., lab- or classroom-level intervention experiment data. Findings from computer simulations might provide useful information regarding how to employ developed interventions and establish educational policies and procedures in diverse educational settings. Hence, these computational approaches can constitute a fundamental part in the conceptual framework of educational neuroscience that bridges the gap between neuroscience and education in practice. It is worth noting that integrating the different levels of analysis for a solution is constrained by the existing breadth of literature. Therefore, it may not be possible to incorporate evidence from all levels of analysis as seen in this moral education example (Fig. 9).

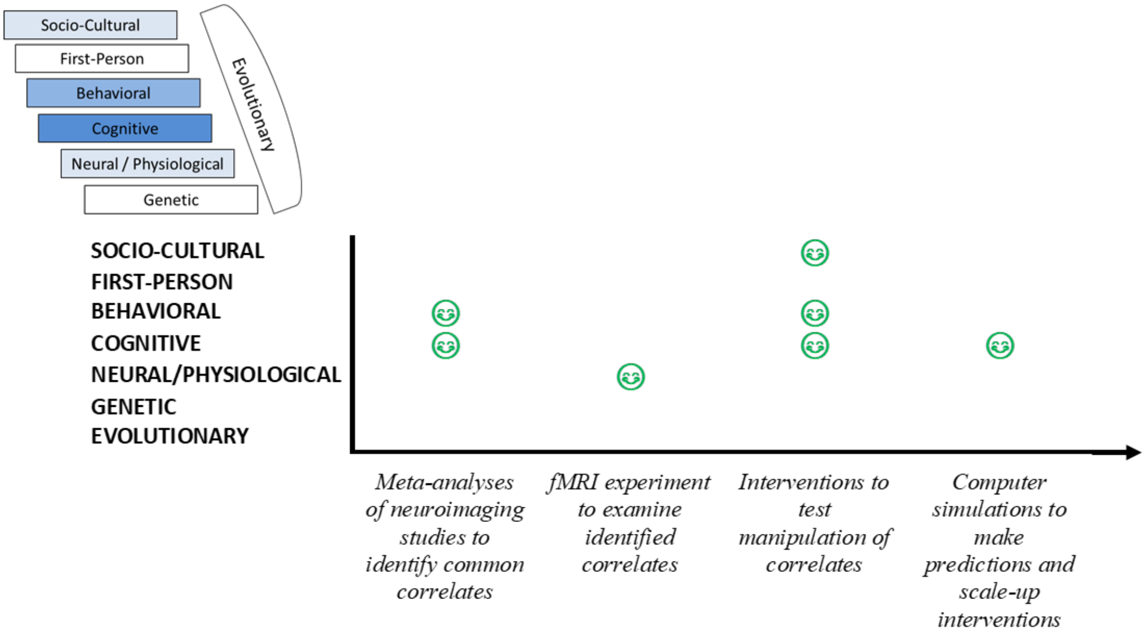

Figure 9. Application of the different levels of analysis within educational neuroscience in the context of the moral education example.

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 a case study 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; 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. 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 in its label from educational neuroscience to a more inclusive term that truly depicts its transdisciplinary nature and integrative power to transform the landscape of learning.

References

[1] S. Chipman, Integrating three perspectives on learning, in: Brain, Cogn. Educ., Academic Press, San Diego, CA, 1986: pp. 203–229.

[2] J.T. Bruer, Education and the brain: A bridge too far, Educ. Res. 26 (1997) 4–16.

[3] J.S. Bowers, The Practical and Principled Problems With Educational Neuroscience, Psychol. Rev. (2016). doi:10.1037/rev0000025.

[4] J.S. Bowers, Psychology, not educational neuroscience, is the way forward for improving educational outcomes for all children: Reply to Gabrieli (2016) and Howard-Jones et al. (2016)., Psychol. Rev. 123 (2016) 628–635. doi:10.1037/rev0000043.

[5] J.D.E. Gabrieli, The promise of educational neuroscience: Comment on Bowers (2016)., Psychol. Rev. 123 (2016) 613–619. doi:10.1037/rev0000034.

[6] P.A. Howard-Jones, S. Varma, D. Ansari, B. Butterworth, B. De Smedt, U. Goswami, D. Laurillard, M.S.C. Thomas, The principles and practices of educational neuroscience: Comment on Bowers (2016)., Psychol. Rev. 123 (2016) 620–627. doi:10.1037/rev0000036.

[7] D. a. Turner, Which part of ‘two way street’ did you not understand? Redressing the balance of neuroscience and education, Educ. Res. Rev. 6 (2011) 223–231.

doi:10.1016/j.edurev.2011.10.002.

[8] D.S. Busso, C. Pollack, No brain left behind: consequences of neuroscience discourse for education, Learn. Media Technol. 40 (2015) 168–186. doi:10.1080/17439884.2014.908908.

[9] D.S. Weisberg, F.C. Keil, J. Goodstein, E. Rawson, J.R. Gray, The seductive allure of neuroscience explanations., J. Cogn. Neurosci. 20 (2008) 470–7. doi:10.1162/jocn.2008.20040.

[10] B. De Smedt, D. Ansari, R.H. Grabner, M.M. Hannula, M. Schneider, L. Verschaffel, Cognitive neuroscience meets mathematics education, Educ. Res. Rev. 5 (2010) 97–105. doi:10.1016/j.edurev.2009.11.001.

[11] L. Mason, Bridging neuroscience and education: a two-way path is possible., Cortex. 45 (2009) 548–9. doi:10.1016/j.cortex.2008.06.003.

[12] G.G. Hruby, Three requirements for justifying an educational neuroscience., Br. J. Educ. Psychol. 82 (2012) 1–23. doi:10.1111/j.2044-8279.2012.02068.x.

[13] J.K. SMITH, L. HESHUSIUS, Closing Down the Conversation: The End of the Quantitative-Qualitative Debate Among Educational Inquirers, Educ. Res. (1986). doi:10.3102/0013189X015001004.

[14] D. Ansari, D. Coch, Bridges over troubled waters: education and cognitive neuroscience, Trends Cogn. Sci. 10 (2006) 146–151.

[15] S. Campbell, Educational Neuroscience: New Horizons for Research in Mathematics Education., in: J. Novotná, H. Moraová, M. Krátká, N. Stehlíková (Eds.), Proc. 30th Conf. Int. Gr. Psychol. Math. Educ., PME, Prague, 2006: pp. 257–264. http://eric.ed.gov/?id=ED495203 (accessed July 28, 2014).

[16] D. Marr, Vision: A Computational Investigation into the Human Representation and Processing of Visual Information, Freeman, San Francisco, 1982. http://books.google.com/books?id=EehUQwAACAAJ&printsec=frontcover%5Cn papers2://publication/uuid/FBD15E5F-E503-450B-B059-4C15D54099CE.

[17] R. McClamrock, Marr’s three levels: A re-evaluation, Minds Mach. 1 (1991) 185–196. doi:10.1007/BF00361036.

[18] P. Churchland, T. Sejnowski, Perspectives on cognitive neuroscience, Science (80-.). 242 (1988) 741–745. doi:10.1126/science.3055294.

[19] J.S. Brown, A. Collins, P. Duguid, Situated Cognition and the Culture of Learning, Educ. Res. 18 (1989) 32–42. doi:10.2307/1176008.

[20] S. Barab, K. Squire, Design-Based Research: Putting a Stake in the Ground, J. Learn. Sci. 13 (2004) 1–14. doi:10.1207/s15327809jls1301_1.

[21] M. Merleau-Ponty, Phenomenology of Perception (1945), Trans. Colin Smith. London: Routledge. (1962).

[22] F.J. Varela, Neurophenomenology: A Methodological Remedy for the Hard Problem, J. Conscious. Stud. 3 (1996) 330–349.

[23] E. Thompson, A. Lutz, D. Cosmelli, Neurophenomenology:An Introduction for Neurophilosophers, in: A. Brook Akins, K. (Ed.), Cogn. Brain Philos. Neurosci. Mov., Cambridge University Press, New York and Cambridge, 2005.

[24] R.M. Shiffrin, W. Schneider, Controlled and automatic human information processing: II. Perceptual learning, automatic attending and a general theory., Psychol. Rev. 84 (1977) 127–190. doi:10.1037/0033-295X.84.2.127.

[25] R.J. Dolan, Neuroimaging of Cognition: Past, Present, and Future, Neuron. 60

(2008) 496–502. doi:10.1016/j.neuron.2008.10.038.

[26] M. Ninaus, S.E. Kober, E.V.C. Friedrich, I. Dunwell, S. De Freitas, S. Arnab, M. Ott, M. Kravcik, T. Lim, S. Louchart, F. Bellotti, A. Hannemann, A.G. Thin, R. Berta, G. Wood, C. Neuper, Neurophysiological methods for monitoring brain activity in serious games and virtual environments: a review, Int. J. Technol. Enhanc. Learn. 6 (2014) 78. doi:10.1504/IJTEL.2014.060022.

[27] J.M. Kivikangas, G. Chanel, B. Cowley, I. Ekman, M. Salminen, S. Järvelä, N. Ravaja, A review of the use of psychophysiological methods in game research, J. Gaming Virtual Worlds. 3 (2011) 181–199. doi:10.1386/jgvw.3.3.181_1.

[28] G. Schulte-Körne, K.U. Ludwig, J. el Sharkawy, M.M. Nöthen, B. Müller-Myhsok, P. Hoffmann, Genetics and Neuroscience in Dyslexia: Perspectives for Education and Remediation, Mind, Brain, Educ. 1 (2007) 162–172. doi:10.1111/j.1751-228X.2007.00017.x.

[29] A.T. Poulsen, S. Kamronn, J. Dmochowski, L.C. Parra, L.K. Hansen, EEG in the classroom: Synchronised neural recordings during video presentation, Sci. Rep. 7 (2017) 1–9. doi:10.1038/srep43916.

[30] A. Obersteiner, T. Dresler, K. Reiss, a. C.M. Vogel, R. Pekrun, A.J. Fallgatter, Bringing brain imaging to the school to assess arithmetic problem solving: chances and limitations in combining educational and neuroscientific research, Zdm. 42 (2010) 541–554. doi:10.1007/s11858-010-0256-7.

[31] J.D.E. Gabrieli, Dyslexia: a new synergy between education and cognitive neuroscience., Science. 325 (2009) 280–3. doi:10.1126/science.1171999.

[32] A.M. Dale, Optimal experimental design for event-related fMRI, Hum. Brain Mapp.

8 (1999) 109–114. doi:10.1002/(SICI)1097-0193(1999)8:2/3<109::AID-HBM7>3.0.CO;2-W.

[33] S.A. Bunge, I. Kahn, Cognition: An Overview of Neuroimaging Techniques, in: Encycl. Neurosci., Elsevier, 2009: pp. 1063–1067. doi:10.1016/B978-008045046-9.00298-9.

[34] B.Z. Allison, J. Polich, Workload assessment of computer gaming using a single-stimulus event-related potential paradigm, Biol. Psychol. 77 (2008) 277–283. doi:10.1016/j.biopsycho.2007.10.014.

[35] B. De Smedt, D. Ansari, R.H. Grabner, M. Hannula-Sormunen, M. Schneider, L. Verschaffel, Cognitive neuroscience meets mathematics education: It takes two to Tango, Educ. Res. Rev. 6 (2011) 232–237. doi:10.1016/j.edurev.2011.10.003.

[36] J. Xu, H. Ma, Applications of URANS on predicting unsteady turbulent separated flows, Acta Mech. Sin. Xuebao. 25 (2009) 319–324. doi:10.1007/s10409-008-0217-3.

[37] C.G. Lim, T.S. Lee, C. Guan, D.S.S. Fung, Y. Zhao, S.S.W. Teng, H. Zhang, K.R.R. Krishnan, A Brain-Computer Interface Based Attention Training Program for Treating Attention Deficit Hyperactivity Disorder, PLoS One. 7 (2012) e46692. doi:10.1371/journal.pone.0046692.

[38] A. Stopczynski, C. Stahlhut, J.E. Larsen, M.K. Petersen, L.K. Hansen, The Smartphone Brain Scanner: A Portable Real-Time Neuroimaging System, PLoS One. 9 (2014) e86733. doi:10.1371/journal.pone.0086733.

[39] T.R. Mullen, C.A.E. Kothe, Y.M. Chi, A. Ojeda, T. Kerth, S. Makeig, T.-P. Jung, G. Cauwenberghs, Real-time neuroimaging and cognitive monitoring using

wearable dry EEG, IEEE Trans. Biomed. Eng. 62 (2015) 2553–2567. doi:10.1109/TBME.2015.2481482.

[40] E. Thompson, Neurophenomenology and Contemplative Experience, in: P. Clayton (Ed.), Oxford Handb. Sci. Relig., Oxford University Press, 2006.

[41] J.R. Rest, D. Narvaez, M. Bebeau, S. Thoma, A Neo-Kohlbergian approach: The DIT and schema theory, Educ. Psychol. Rev. 11 (1999) 291–324. doi:10.1023/a:1022053215271.

[42] T.A. Ito, J.T. Cacioppo, Attitudes as Mental and Neural States of Readiness: Using Physiological Measures to Study Implicit Attitudes, in: B.W.N. Schwarz (Ed.), Implicit Meas. Attitudes, Guilford Press, New York, NY, US, 2007: pp. 125–158.

[43] K. Kristjánsson, Virtues and Vices in Positive Psychology: A Philosophical Critique, Cambridge University Press, New York, NY, 2013.

[44] H. Han, How can neuroscience contribute to moral philosophy, psychology and education based on Aristotelian virtue ethics?, Int. J. Ethics Educ. (2016). doi:10.1007/s40889-016-0016-9.

[45] D.T. Miller, D.A. Prentice, Psychological Levers of Behavior Change, in: E. Shafir (Ed.), Behav. Found. Public Policy, Princeton University Press, Princeton, NJ, 2012: pp. 301–309.

[46] S.G. Costafreda, Pooling FMRI data: meta-analysis, mega-analysis and multi-center studies., Front. Neuroinform. 3 (2009) 33. doi:10.3389/neuro.11.033.2009.

[47] A. Etkin, T.D. Wager, Functional neuroimaging of anxiety: a meta-analysis of emotional processing in PTSD, social anxiety disorder, and specific phobia., Am. J. Psychiatry. 164 (2007) 1476–1488. doi:10.1176/appi.ajp.2007.07030504.

[48] T.D. Wager, J. Jonides, S. Reading, Neuroimaging studies of shifting attention: a meta-analysis., Neuroimage. 22 (2004) 1679–1693. doi:10.1016/j.neuroimage.2004.03.052.

[49] R.A. Poldrack, Inferring mental states from neuroimaging data: From reverse inference to large-scale decoding, Neuron. 72 (2011) 692–697. doi:10.1016/j.neuron.2011.11.001.

[50] S.B. Eickhoff, D. Bzdok, A.R. Laird, F. Kurth, P.T. Fox, Activation likelihood estimation meta-analysis revisited, Neuroimage. 59 (2012) 2349–2361. doi:10.1016/j.neuroimage.2011.09.017.

[51] S.B. Eickhoff, A.R. Laird, C. Grefkes, L.E. Wang, K. Zilles, P.T. Fox, Coordinate-based activation likelihood estimation meta-analysis of neuroimaging data: a random-effects approach based on empirical estimates of spatial uncertainty., Hum. Brain Mapp. 30 (2009) 2907–2926.

[52] D. Bzdok, L. Schilbach, K. Vogeley, K. Schneider, A.R. Laird, R. Langner, S.B. Eickhoff, Parsing the neural correlates of moral cognition: ALE meta-analysis on morality, theory of mind, and empathy, Brain Struct. Funct. 217 (2012) 783–796. doi:10.1007/s00429-012-0380-y.

[53] G. Sevinc, R.N. Spreng, Contextual and Perceptual Brain Processes Underlying Moral Cognition: A Quantitative Meta-Analysis of Moral Reasoning and Moral Emotions, PLoS One. 9 (2014) e87427. doi:10.1371/journal.pone.0087427.

[54] M. Boccia, C. Dacquino, L. Piccardi, P. Cordellieri, C. Guariglia, F. Ferlazzo, S. Ferracuti, A.M. Giannini, Neural foundation of human moral reasoning: an ALE meta-analysis about the role of personal perspective, Brain Imaging Behav. (2016).

doi:10.1007/s11682-016-9505-x.

[55] B. Garrigan, A.L.R. Adlam, P.E. Langdon, The neural correlates of moral decision-making: A systematic review and meta-analysis of moral evaluations and response decision judgements, Brain Cogn. 108 (2016) 88–97. doi:10.1016/j.bandc.2016.07.007.

[56] H. Han, Neural correlates of moral sensitivity and moral judgment associated with brain circuitries of selfhood: A meta-analysis, J. Moral Educ. (2017). doi:10.1080/03057240.2016.1262834.

[57] J.R. Rest, Postconventional moral thinking : a Neo-Kohlbergian approach, Lawrence Erlbaum Associates, Publishers, Mahwah, NJ, 1999.

[58] J.R. Rest, D. Narváez, Moral development in the professions : psychology and applied ethics, Lawrence Erlbaum Associates, Inc, Mahwah, NJ, 1994. doi:10.5860/CHOICE.32-5012.

[59] J.D. Greene, L.E. Nystrom, A.D. Engell, J.M. Darley, J.D. Cohen, The neural bases of cognitive conflict and control in moral judgment, Neuron. 44 (2004) 389–400. doi:10.1016/j.neuron.2004.09.027.

[60] D. Robertson, J. Snarey, O. Ousley, K. Harenski, F. DuBois Bowman, R. Gilkey, C. Kilts, The neural processing of moral sensitivity to issues of justice and care., Neuropsychologia. 45 (2007) 755–66. doi:10.1016/j.neuropsychologia.2006.08.014.

[61] K. Prehn, I. Wartenburger, K. Meriau, C. Scheibe, O.R. Goodenough, A. Villringer, E. Van der Meer, H.R. Heekeren, Individual differences in moral judgment competence influence neural correlates of socio-normative judgments, Soc. Cogn.

Affect. Neurosci. 3 (2008) 33–46. doi:10.1093/Scan/Nsm037.

[62] K.J. Yoder, J. Decety, The Good, the bad, and the just: justice sensitivity predicts neural response during moral evaluation of actions performed by others., J. Neurosci. 34 (2014) 4161–6. doi:10.1523/JNEUROSCI.4648-13.2014.

[63] J. Decety, K.J. Michalska, K.D. Kinzler, The contribution of emotion and cognition to moral sensitivity: a neurodevelopmental study., Cereb. Cortex. 22 (2012) 209–20. doi:10.1093/cercor/bhr111.

[64] J. Moll, R. de Oliveira-Souza, F.T. Moll, F.A. Ignácio, I.E. Bramati, E.M. Caparelli-Dáquer, P.J. Eslinger, The moral affiliations of disgust: a functional MRI study., Cogn. Behav. Neurol. 18 (2005) 68–78. doi:00146965-200503000-00008 [pii].

[65] P. Michl, T. Meindl, F. Meister, C. Born, R.R. Engel, M. Reiser, K. Hennig-Fast, Neurobiological underpinnings of shame and guilt: a pilot fMRI study., Soc. Cogn. Affect. Neurosci. 9 (2014) 150–7. doi:10.1093/scan/nss114.

[66] J. Decety, E.C. Porges, Imagining being the agent of actions that carry different moral consequences: An fMRI study, Neuropsychologia. 49 (2011) 2994–3001. doi:10.1016/j.neuropsychologia.2011.06.024.

[67] J. Decety, C. Chen, C.L. Harenski, K.A. Kiehl, Socioemotional processing of morally-laden behavior and their consequences on others in forensic psychopaths, Hum. Brain Mapp. (2015). doi:10.1002/hbm.22752.

[68] J. Moll, R. De Oliveira-Souza, G.J. Garrido, I.E. Bramati, E.M.A. Caparelli-Daquer, M.L.M.F. Paiva, R. Zahn, J. Grafman, The self as a moral agent: linking the neural bases of social agency and moral sensitivity., Soc. Neurosci. 2 (2007) 336–352. doi:10.1080/17470910701392024.

[69] H. Han, J. Chen, C. Jeong, G.H. Glover, Influence of the Cortical Midline Structures on Moral Emotion and Motivation in Moral Decision-Making, Behav. Brain Res. (2016). doi:10.1016/j.bbr.2016.01.001.

[70] K.J. Friston, A.P. Holmes, K.J. Worsley, J.-P. Poline, C.D. Frith, R.S.J. Frackowiak, Statistical parametric maps in functional imaging: A general linear approach, Hum. Brain Mapp. 2 (1995) 189–210. doi:10.1002/hbm.460020402.

[71] A.K. Seth, A.B. Barrett, L. Barnett, Granger Causality Analysis in Neuroscience and Neuroimaging, J. Neurosci. 35 (2015) 3293–3297. doi:10.1523/JNEUROSCI.4399-14.2015.

[72] V. Menon, L.Q. Uddin, Saliency, switching, attention and control: a network model of insula function NIH Public Access Author Manuscript Introduction and overview, Brain Struct. Funct. 214 (2010) 655–667. doi:10.1007/s00429-010-0262-0.

[73] D.S. Yeager, G.M. Walton, Social-Psychological Interventions in Education: They're Not Magic, Rev. Educ. Res. 81 (2011) 267–301. doi:10.3102/0034654311405999.

[74] D.S. Yeager, K.H. Trzesniewski, C.S. Dweck, An Implicit Theories of Personality Intervention Reduces Adolescent Aggression in Response to Victimization and Exclusion, Child Dev. 84 (2013) 970–988. doi:10.1111/cdev.12003.

[75] D.S. Yeager, K.H. Trzesniewski, K. Tirri, P. Nokelainen, C.S. Dweck, Adolescents' Implicit Theories Predict Desire for Vengeance after Peer Conflicts: Correlational and Experimental Evidence, Dev. Psychol. 47 (2011) 1090–1107.

[76] G.L. Cohen, J. Garcia, V. Purdie-Vaughns, N. Apfel, P. Brzustoski, Recursive

Processes in Self-Affirmation: Intervening to Close the Minority Achievement Gap, Science (80-.). 324 (2009) 400–403.

[77] G.L. Cohen, J. Garcia, Identity, Belonging, and Achievement: A Model, Interventions, Implications, Curr. Dir. Psychol. Sci. 17 (2008) 365–369.

[78] K. Kristjánsson, Emulation and the use of role models in moral education, J. Moral Educ. 35 (2006) 37–49.

[79] W. Sanderse, The meaning of role modelling in moral and character education, J. Moral Educ. (2012) 1–15. doi:10.1080/03057240.2012.690727.

[80] A. Bandura, F.J. McDonald, Influence of social reinforcement and the behavior of models in shaping children's moral judgments, J. Abnorm. Soc. Psychol. 67 (1963) 274–281.

[81] J. Haidt, The positive emotion of elevation, Prev. Treat. 3 (2000) 1–5.

[82] Z.A. Englander, J. Haidt, J.P. Morris, Neural basis of moral elevation demonstrated through inter-subject synchronization of cortical activity during free-viewing, PLoS One. 7 (2012) e39384. doi:10.1371/journal.pone.0039384.

[83] R.H. Smith, Assimilative and contrastive emotional reactions to upward and downward social comparisons, in: J. Suls, L. Wheeler (Eds.), Handb. Soc. Comp. Theory Res., Kluwer Academic/Plenum Publishers, New York, 2000: pp. 173–200.

[84] J. Suls, R. Martin, L. Wheeler, Social comparison: Why, with whom, and with what effect?, Curr. Dir. Psychol. Sci. 11 (2002) 159–163. doi:10.1111/1467-8721.00191.

[85] B. Monin, Holier than me? Threatening social comparison in the moral domain, Rev. Int. Psychol. Soc. 20 (2007) 53–68.

[86] B. Monin, P.J. Sawyer, M.J. Marquez, The rejection of moral rebels: resenting those

who do the right thing., J. Pers. Soc. Psychol. 95 (2008) 76–93. doi:10.1037/0022-3514.95.1.76.

[87] M.D. Alicke, Evaluating social comparison targets, in: J. Suls, L. Wheeler (Eds.), Handb. Soc. Comp. Theory Res., Kluwer Academic/Plenum Publishers, New York, 2000: pp. 271–293.

[88] J. V. Wood, Theory and research concerning social comparisons of personal attributes., Psychol. Bull. 106 (1989) 231–248. doi:10.1037/0033-2909.106.2.231.

[89] H. Han, J. Kim, C. Jeong, G.L. Cohen, Attainable and Relevant Moral Exemplars Are More Effective than Extraordinary Exemplars in Promoting Voluntary Service Engagement, Front. Psychol. 8 (2017) 283. doi:10.3389/fpsyg.2017.00283.

[90] G.M. Walton, G.L. Cohen, D. Cwir, S.J. Spencer, Mere Belonging: The Power of Social Connections, J. Pers. Soc. Psychol. 102 (2012) 513–532.

[91] R.B. Cialdini, Full-cycle social psychology., Appl. Soc. Psychol. Annu. 1 (1980) 21–47.

[92] P. Lockwood, Z. Kunda, Superstars and me: Predicting the impact of role models on the self., J. Pers. Soc. Psychol. 73 (1997) 91–103. doi:10.1037/0022-3514.73.1.91.

[93] G.M. Walton, G.L. Cohen, A brief social-belonging intervention improves academic and health outcomes of minority students, Science (80-.). 331 (2011) 1447–1451. doi:10.1126/science.1198364.

[94] D.S. Yeager, C.J. Fong, H.Y. Lee, D.L. Espelage, Declines in efficacy of anti-bullying programs among older adolescents: Theory and a three-level meta-analysis, J. Appl. Dev. Psychol. 37 (2015) 36–51. doi:10.1016/j.appdev.2014.11.005.

[95] A.L. Brown, Design Experiments: Theoretical and Methodological Challenges in Creating Complex Interventions in Classroom Settings, J. Learn. Sci. 2 (1992) 141–178. doi:10.1207/s15327809jls0202_2.

[96] N. Claidière, T.C. Scott-Phillips, D. Sperber, How Darwinian is cultural evolution?, Philos. Trans. R. Soc. Lond. B. Biol. Sci. 369 (2014) 20130368. doi:10.1098/rstb.2013.0368.

[97] L. Deng, D. Yu, Deep learning: Methods and applications, Found. Trends® Signal Process. 7 (2014) 197–387. doi:10.1561/2000000039.

[98] N. Claidière, Darwinian theories of cultural evolution: models and mechanisms, Ecole Normale Supeieure & Universite Pierre et Marie Curie, 2009.

[99] H. Han, K. Lee, F. Soylu, Predicting Long-term Outcomes of Educational Interventions Using the Evolutionary Causal Matrices and Markov Chain Based on Educational Neuroscience, Trends Neurosci. Educ. 5 (2016) 157–165. doi:10.1016/j.tine.2016.11.003.

[100] H. Han, K. Lee, F. Soylu, Simulating outcomes of interventions using a multipurpose simulation program based on the evolutionary causal matrices and Markov chain, Knowl. Inf. Syst. (2018). doi:10.1007/s10115-017-1151-0.

[101] J. Cohen, Statistical power analysis for the behavioral sciences, 1988. doi:10.1234/12345678.

[102] M. Abadi, A. Agarwal, P. Barham, E. Brevdo, Z. Chen, C. Citro, G.S. Corrado, A. Davis, J. Dean, M. Devin, S. Ghemawat, I. Goodfellow, A. Harp, G. Irving, M. Isard, Y. Jia, R. Jozefowicz, L. Kaiser, M. Kudlur, J. Levenberg, D. Mane, R. Monga, S. Moore, D. Murray, C. Olah, M. Schuster, J. Shlens, B. Steiner, I. Sutskever, K.

Talwar, P. Tucker, V. Vanhoucke, V. Vasudevan, F. Viegas, O. Vinyals, P. Warden, M. Wattenberg, M. Wicke, Y. Yu, X. Zheng, TensorFlow: Large-Scale Machine Learning on Heterogeneous Distributed Systems, Mountain View, CA, 2015.

[103] H. Han, Attainable and Relevant Moral Exemplars as Powerful Sources for Moral Education: From Vantage Points of Virtue Ethics and Social Psychology, in: Invit. Oral Present. 4th Annu. Conf. Jubil. Cent. Character Virtues, Oxford, UK, 2016.