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Neuroscientific Perspectives on Poverty

Courtney Stevens, Eric Pakulak, María Soledad Segretin & Sebastián J. Lipina, ***Editors***

NEUROSCIENTIFIC PERSPECTIVES ON POVERTY

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Sebastián J. Lipina

(Editors)

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FORWARD

Antonio M. Battro

The *Ettore Majorana Foundation and Center for Scientific Culture* [1] (EMFCSC), whose headquarters are located in the Sicilian city of Erice, was founded in 1962 by Professor Antonino Zichichi. Zichichi was Professor Emeritus of Physics at the University of Bologna, member of the European Organization for Nuclear Research (CERN), President of the World Federation of Scientists (WFS), and the author of numerous high-impact investigations in the world of sub-nuclear physics. Initially, the EMFCSC was proposed as a meeting center for physicists from countries with advanced developments in nuclear research. In later years such encounters were extended to other disciplines. Since its establishment, hundreds of scientists -among them more than a hundred Nobel Prize laureates- have attended the Foundation's different scientific schools, for which Erice has been given the name *City of Sciences*. From there emerged the *Declaration of a Science for Peace* in 1982, which promotes a science without secrets and

[1] http://www.ccsem.infn.it/

without borders, and which has collected more than 90,000 signatures from scientists from 140 countries[2].

With the creation of the EMFCSC, Professor Zichichi honored Ettore Majorana, a prodigy physicist originally from Catania (Sicily) and an outstanding disciple of Enrico Fermi. Majorana died at a young age in 1938 during a trip from Palermo to Naples, where he served as a professor. It is not known under what circumstances Majorana disappeared, because he never reached his destination. This dramatic and intriguing story was masterfully told by the Sicilian writer Leonardo Sciascia in his book *The Disappearance of Majorana*. Indeed, Sicily is an island of mysteries; and Erice, built on the majestic San Giuliano mountain (Figure 1), is a treasure of stories and home for new and unexpected friendships founded on scientific culture.

Figure 1 – Panoramic view of the northwestern coast of Sicily from Erice Castle (Photo by Sebastián J. Lipina).

At the beginning of the last decade, Professor Zichichi invited me to visit his center in Erice to establish a new school in the field of research that we were conducting together with Professor Kurt W. Fischer at the Graduate School of Education at Harvard University. We gladly accepted their generous offer and decided to open an annual course for the *International School on*

[2] http://www.ccsem.infn.it/em/erice_statement/index.html

Mind, Brain, and Education in 2005. Since then, more than two hundred guests from all continents have participated in the school. The result of these weeks of work are the publications that have emerged from our presentations and discussions, many of them in the journal *Mind, Brain, and Education*, which we founded with Kurt Fisher and other colleagues at Harvard University in 2007, as an organ of the *International Mind, Brain, and Education Society* (IMBES).

In addition to exchanging information and disseminating our research, Erice inspires us to establish new contacts, propose collaborative projects, consolidate solid international relationships, and, in many cases, start a true friendship between colleagues from different generations. In 2017, Sebastián Lipina gathered in Erice a group of scientists involved in the neuroscientific and cognitive study of poverty. In collaboration with Eric Pakulak, María Soledad Segretin, and Lourdes Majdalani, Sebastián Lipina carefully created a program of presentations and discussions which were conducted between the 2nd and 6th of September in the luminous setting of the Richard P. Feynman Room of the old San Rocco monastery, currently the Institute Isidor I. Rabi and headquarters of the EMFCSC (Figure 2).

Figure 2 – Presentation of Professor Courtney Stevens (Willamette University) in the Feynman room of the San Rocco monastery (Photo by Sebastián J. Lipina).

I want to thank all the participants of the *Neuroscience of Poverty* course for the publication of their valuable contributions in this book, which inaugurates a new stage in our annual courses.

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IMPLICATIONS OF THE NEUROSCIENTIFIC EVIDENCE ON CHILDHOOD POVERTY

Sebastián J. Lipina and M. Soledad Segretin

Introduction

Over the past two decades, research on childhood poverty has begun to provide evidence that contributes to advancing the understanding of how early adversity associated with material and social deprivation impacts brain development. When such evidence is used in other disciplinary contexts, references are typically made to early brain development as a predictor of either adaptive behaviors and economic productivity during adult life (e.g., Black el al., 2017) or of the impossibility of such achievements due to the supposed immutability of the long-term negative impacts of childhood poverty on brain development (Nilsen, 2017). These types of statements, which have not only scientific but also policy implications, need to be analyzed adequately in light of the available evidence, as they could lead to misconceptions and overgeneralizations that have the potential to affect investment criteri a, as well as the design, implementation, and evaluation of actions in the field of early childhood.

Consequently, in addition to the need to review the available evidence we consider it important to create opportunities for critical reflection that contribute to understanding the implications of this evidence. This chapter addresses three aspects that we consider essential for these aims: (1) a brief review of the basic concepts of human development proposed by contemporary developmental science; (2) a synthesis of the neuroscientific evidence from poverty studies; and (3) a reflection on the implications of such evidence for the continuity of the construction of knowledge in the area, as well as for the design, implementation, and evaluation of interventions or policies.

Assumptions about human development

Systemic-relational approaches

Contemporary theories of human development are framed within meta-theoretical frameworkds called relational development systems (RDS), which propose that changes that occur during the life cycle occur through relationships of mutual influence between people and their developmental contexts (Overton & Molenaar, 2016). This type of approach deals with analyzing: (a) processes (i.e., changes in developmental systems); (b) experiences (i.e., developmental processes occur over time, which implies that they take the form of states of potentiality and action); (c) systems (i.e., social and cultural contexts in which developmental processes occur); (d) relational analysis of mutual influences between individuals and contexts; and (e) multiplicity of perspectives and forms of explanation. Consequently, what characterizes development is the permanent co-evolution or transformation of the biological and social systems it involves, so that the directionality of the trajectories is variable between individuals and populations, within the limits imposed by the regularities of species.

Likewise, RDS approaches deal with analyzing different levels of organization, from the biological to the cultural (Barker, 1965; Bronfenbrenner, 1987; Lerner, 2018), so that the interactions between people and contexts are both independent and interdependent (Figure 1). The individual is considered a complex, active, and self-regulating agent. Given such a self-regulatory characteristic, any notion of adaptation necessarily requires considering contextual meanings: there would be no adaptation processes independent of the contexts in which they occur - which includes the belief systems, norms, and values that characterize every culture.

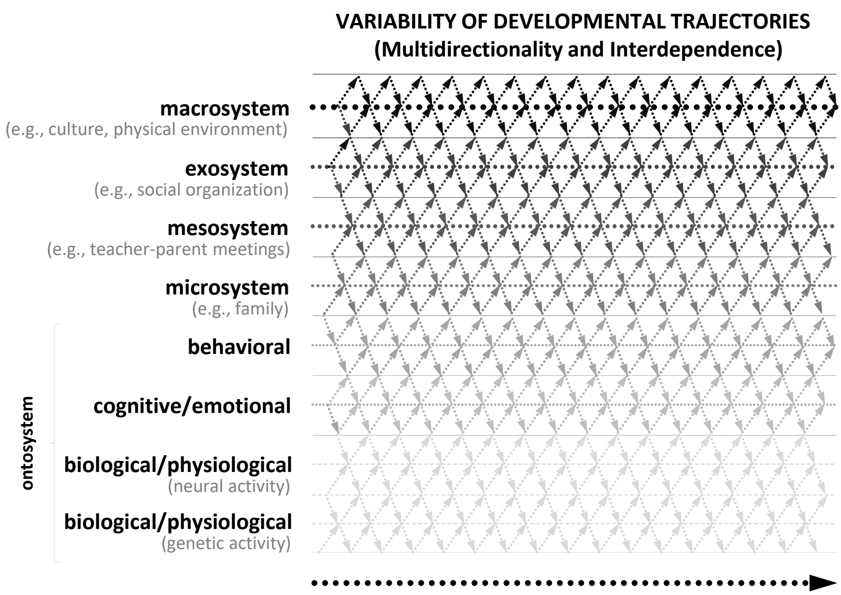

Figure 1 – Schematic representation of an RDS model that theoretically illustrates the matrix of possible trajectories, relationships and interactions of developmental events considering different levels of organization defined in terms of contexts according to the theory of Urie

Bronfenbrenner (i.e., ontosystemic, microsystemic, mesosystemic, exosystemic, macrosystemic). For the same individual, at each level of organization a trajectory of events could be drawn that would be idiosyncratic with respect to the mechanisms that occur there; and at the same time interdependent of the trajectories at other levels (inspired by Figure 2.1 of Lerner, 2018).

Neural development

The initial organization of the nervous system follows a sequence of adaptive processes of generation, connection, and elimination of nerve cells and connections. The initial phases of nerve cell generation, migration, and subsequent differentiation are followed by dendritic growth, synapse formation, and elimination. The further development and refinement of neural networks almost always involves the removal of neurons through a programmed process called apoptosis. At the end of these initial processes of organization of the nervous system, about half of the neurons are finally eliminated. The evidence available from five decades of research indicates that the timing of such processes of overproduction and pruning of synaptic contacts varies in different areas of the cerebral cortex, continuing through at least the second decade of life (Bathelt et al., 2018; Brown, 2017; Ismail et al., 2017; Perez et al., 2016; Schmitt et al., 2017).

In studies with animal models, the presence or absence of material, sensory, and social stimuli in developmental contexts has been repeatedly associated with changes in different aspects of the structure and functioning of the nervous system during its development. Such changes, which occur due to the adaptive nature of the components and connections of the nervous system, have been documented at different levels of organization, from the molecular to the structure and function of different neural networks (Caroni et al., 2012; Grossman et al ., 2003). In humans, these development processes are modulated by a great diversity of molecular, cellular, psychological, social, and cultural mechanisms.

During neural development, there are moments of maximum organization of different functions that are called *critical or sensitive periods*, and that occur at different times for different neural networks. If during such critical periods an alteration occurs, either positive or negative, it will tend to be incorporated into the neural function in a permanent or semi-permanent way, limiting the opportunities for its reorganization. Many of these periods take place early in development, particularly during the perinatal phase and in the first months of life. In the case of more complex processes such as emotional, cognitive, and learning skills, such organization depends on the progressive integration of different neural networks, which process more than one modality of information and which take place at different times during at least the two first decades of life. At the neural level, this integration requires different types of nutrients and experiences that include but extend well beyond the first thousand days (Figure 2). From the contemporary perspective of neural development, the first thousand days are extremely insufficient to predict the development of a typical human brain. In summary, the available neuroscientific knowledge allows us to affirm that, from conception and throughout life, the nervous system is organized and modified based on the dynamic interaction between individual and contextual characteristics of each person.

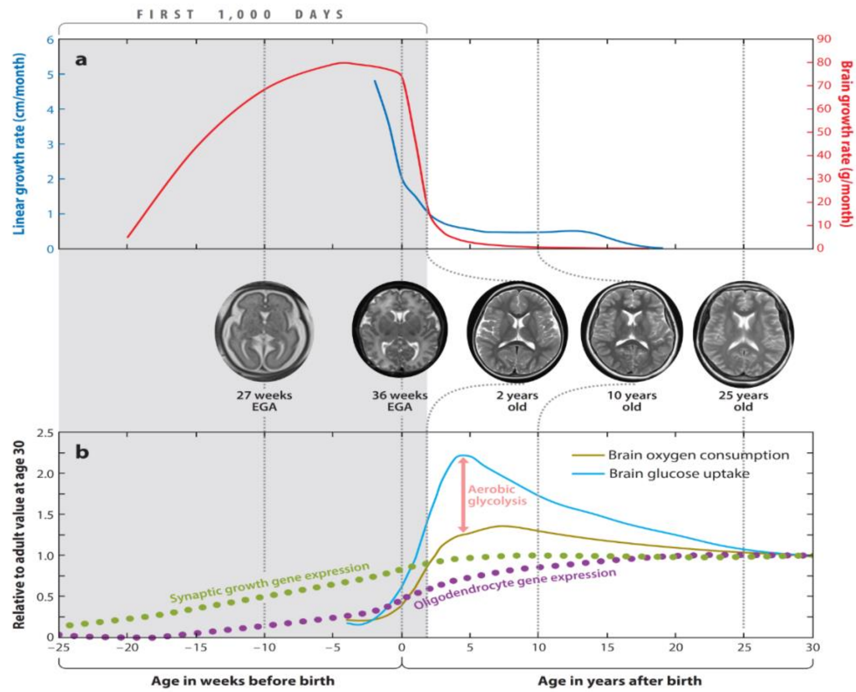

Figure 2 - Significant changes in the human brain from conception to adulthood. The human brain gains much of its mass and structure during the first thousand days, which begin at conception and end at approximately 2 years of age. (a) The brain growth rate (red line) is very high during this period of time, and then falls rapidly as childhood begins. Structurally, the brain also begins to closely resemble the adult brain at 2 years of age. Metaphorically, the foundation, structure, and framework of the construction process have been largely completed. However, much more work needs to be done to build, reshape, and isolate the myriad of connections within the brain. (b) Gene expression related to synaptic growth peaks shortly after the first 1,000 days, but remains high into adulthood (green dotted line). The genetic expression related to myelination increases later in time (purple dotted line). Both the consumption of oxygen in the brain (green solid line) and glucose (blue light solid line) continue to increase and reach their maximum level in early childhood, gradually decreasing to adult levels during the rest of childhood and adolescence. In particular, the gap between glucose and oxygen consumption widens: aerobic glycolysis at 5 years represents approximately 30% of the glucose consumption rate of the human brain

compared to approximately 10% at the age of 30. These characteristics point to the important metabolic requirements of the brain that continue well beyond the first 1,000 days, advocating an expanded perspective on the nutritional requirements of the developing human brain. Abbreviation: EGA, estimated gestational age. This figure corresponds to the work by Goyal et al., 2018, and authorized for reproduction in this chapter by its authors.

Summary of neuroscientific evidence on childhood poverty [3]

Studies on association between poverty and neural events

The neuroscientific study of childhood poverty is a recently developed area (Farah, 2017, 2018; Lipina & Colombo, 2009). Since the mid-1990s, different researchers began to compare the performance of children from homes with and without poverty in tasks with self-regulatory, phonological processing, and episodic memory demands. Neuroimaging and behavioral genetics technologies were gradually incorporated into such efforts. The first investigations with this type of information began to be published only in the 2000s. Until mid-2019, the number of published studies presenting empirical evidence generated with neuroimaging did not exceed the number of 200 articles in two decades. On the other hand, approximately 80% of such evidence was generated in the United States, 77% of the studies applied cross-sectional designs, 50% of articles were based on anatomical information, and less than 5% addressed issues related to learning

[3] In this chapter we will not address specific questions inherent in the conceptual definitions and indicators of poverty -a topic that raises different debates and complexities of analysis in different human and social disciplines for decades- for which we will refer to the term poverty to all the forms of material and social deprivation derived from processes of inequity. Readers interested in delving into such specific questions will find more than two hundred definitions and indicators in the work by Spickler and colleagues (2009), which contains definitions and paradigms that have generated in the social, human, and health sciences since the late nineteenth century.

(Farah, 2018; Lipina, 2017a). This publication profile does not in any way detract from the area's effort to contribute to knowledge. However, it is important to understand what kinds of statements can and cannot be supported, since an important part of the contemporary narrative on neural development does not incorporate the update of the evidence generated during the 1990s (Lipina, 2016, 2017c) .

The main current questions in the area focus on some topics already discussed in the fields of developmental psychology, cognitive psychology, and health sciences for much of the 20th century, especially with respect to the effects and mechanisms of mediation at the level of behavioral organization. However, the innovative aspect of neuroscientific approaches in childhood poverty studies is the consideration of components, events, and mechanisms related to processes of cognitive and emotional self-regulation, phonological processing, memory, and learning, at the neural level of organization (D´Angiulli et al., 2014; Farah, 2017, 2018; Johnson et al., 2016; Lipina, 2016, 2017b; Pakulak et al., 2018; Ursache & Noble, 2016) [4].

At the behavioral level of organization, evidence indicates that poverty is associated with low performance on tasks with demands for cognitive control and metacognitive processes (e.g., executive functions and theory of mind), phonological processing, episodic memory, and learning, and these effects are observed at least through the first two decades of life (Farah, 2017; Johnson et al., 2016; Lipina & Colombo, 2009). In some studies, it has been

[4] The influences of prenatal and postnatal exposure to malnutrition, legal and illegal drugs, and environmental toxic agents on neural development are aspects related, although not exclusively so, to the experience of childhood poverty. For this reason, we will not address this evidence in this chapter, as we will focus our attention on specific studies in neuroscience and childhood poverty. However, readers who wish to access such information may consult the works of Donald et al. (2015), Georgieff et al. (2015), Grandjean and Landrigan (2014), Thompson et al. (2009), and Wiebe et al. (2015).

verified that the association of exposure to poverty with performance in some cognitive tasks is neither similar across all domains, nor uniform for all ages (e.g., Farah et al., 2006; Lipina et al., 2013; Noble, Norman, & Farah, 2005). This means that there are children living in conditions of adversity due to poverty who have typical performances for their age in some cognitive domains, and that this may vary according to their age and the type of test administered. This is to be expected, since both poverty and self-regulatory development are complex processes that involve multiple interdependent factors.

Evidence at the behavioral level of organization is invaluable to understanding the associations between poverty and self-regulatory development, episodic memory, and learning. However, behavioral studies do not allow inferences to be drawn about the level of neural organization. This requires specific technical and methodological approaches that began to be implemented in the early 2000s, when researchers began to use techniques such as structural magnetic resonance imaging (MRI), magnetic resonance spectroscopy (MRS), and functional magnetic resonance imaging (fMRI), as well as electroencephalography (EEG) and event-related potential (ERP) techniques, and structural and functional infrared spectroscopy (NIRS and fNIRS).

These techniques have been used to obtain different types of information. With MRI, it is possible to obtain high-resolution anatomical images that allow structural aspects of the brain to be measured, such as thickness, surface or volume of gray and white matter, as well as the concentration of neurotransmitters. The association of this type of information with that of performance in cognitive or learning tasks, for example, can only be made through correlational analyses, which are associative and do not account for causal relationships. Beyond this limitation, in this preliminary stage of the studies of the area, such information is valuable to begin to understand phenomena of neural and behavioral plasticity that should continue to be deepened with new research that improves knowledge about the mechanisms involved (Farah, 2018; Lipina, 2016; Pakulak et al., 2018). It is also important to note that information on thickness, surface, and volume of the cerebral cortex obtained with MRI techniques corresponds to a macroscopic dimension of analysis. This means that it does not provide information on molecular and cellular events that also participate in the mechanisms of association between poverty and neural development. Functional MRI techniques allow for the acquisition of information on the neural resources involved during the performance of tasks, based on the increase in neural activity due to oxygen consumption. Electroencephalographic techniques allow for the acquisition of information on neuronal electrical activity in the resting state (EEG) or in response to specific stimuli (ERP). NIRS techniques are based on the detection of near infrared light through the skull, which permits non-invasive assessment of brain structure and, via detection of changes in blood oxygenation associated with neural activity in a manner similar to fMRI, brain function.

These different neuroimaging techniques vary in the nature and quality of information they each provide with respect to spatial and temporal resolution. In the case of fMRI, it is important for the non-expert reader to understand that in images where color is used to denote areas of greater activity, these colors are assigned by the researchers after carrying out different statistical analyses. In turn, all the techniques require a great deal of filtering of noisy signals, which involves specific conceptual and methodological criteria for decision-making processes. In other words, such images are in part the construction of researchers. With the exception of MRS or high resolution equipment, in general these techniques provide information at the macroscopic level.

A summary of the evidence from MRI studies indicates that family income and maternal education have been associated with changes in the volume of the hippocampus and the amygdala between the ages of 4 and 22 years. On the other hand, maternal educational level has been associated with a larger range of outcomes, including differences in the following: changes in the cortical thickness and the volume of the prefrontal, parietal, and occipital neural networks between the ages of 4 and 18 years; the rate of brain growth and in the volume of frontal and parietal neural networks in children from 1 month to 4 years of age; the connectivity between frontal and parietal neural networks between 12 and 24 years of age; and the trajectories of the development of neural networks of the hippocampus in girls and adolescents from 9 to 15 years old. Finally, parental income and education have been associated with changes in the patterns of connectivity between different cortical neural networks and the striatum between the ages of 6 and 17 (Avants et al., 2015; Betancourt et al., 2015; Brito et al., 2017; Ellwood-Lowe et al., 2018; Hair et al., 2015; Mackey et al., 2015; Marshall et al., 2018; Noble et al., 2015; Piccolo et al., 2016; Sripada et al., 2014; Ursache et al., 2016; Weissman et al., 2018). In some of these studies, structural changes were also associated with performance on tasks with demands for cognitive control, language, and learning (e.g., Brito et al., 2017; Hair et al., 2015; Mackey et al., 2015; Noble, et al., 2015; Ursache et al., 2016).

Only recently has MRI evidence begun to be generated on the association between poverty and neural development in adult populations without histories of neurological or psychiatric disorders. For instance, McLean and colleagues (2012) found that the history of childhood poverty in terms of material deprivation was associated with changes in the concentration of N-Acetyl-aspartate (NAA), a molecular marker associated with neuronal integrity, in neural networks of the hippocampus of adults from 35 to 65 years. Chan and colleagues (2018) found that lower educational and occupational level in a sample of adults aged 35 to 64 years was associated with a reduction in the organization of functional brain networks and cortical thickness - such associations were present even when controlling for childhood socioeconomic status. In addition, preliminary evidence in studies with adults suggests that the processes of accumulation of adversities during the life cycle are not necessarily linear (Chan et al., 2018; Hackman & Farah, 2009).

Results from fMRI studies have found that income, maternal education, and paternal occupation were associated with changes in the activation of occipito-temporal networks during tasks with phonological processing demands in children between 4 and 8 years of age; the activation of prefrontal networks during the performance of tasks with associative learning demands in children between 4 and 8 years of age; activation of prefrontal and parietal networks during tasks with working memory and arithmetic processing demands in children between 8 and 12 years of age ; and the activation of amygdala networks during the performance of tasks in which threatening faces must be processed, in adults from 23 to 25 years old with a history of childhood poverty (Finn et al., 2016; Javanbakht et al., 2015; Noble et al., 2006; Raizada et al., 2008; Sheridan et al., 2012).

In EEG/ERP studies, evidence indicates that family income, maternal education, and paternal occupation have been associated with changes in: electrical activity during the resting state of infants between 6 and 9 months old; the ERP associated with attentional control of irrelevant information in children from 3 to 8 years of age; the electrical activity associated with the processing of speech and environmental sounds in adolescents; the frontal potentials related to the detection of errors and in theta power in children aged 16 to 18 months and 4 years; and the prediction of cognitive performance at 15 months based on electrical activity in the resting state at one month of life (Brito et al., 2016; Conejero et al., 2016; D´Angiulli et al., 2012; Skoe et al., 2013; Stevens et al., 2009; Tomalski et al., 2013).

This evidence confirms that poverty measured in terms of family income, parental education and occupation, and material deprivation - indicators that do not specifically account for everything included in the child's experience of poverty - are associated with a diverse set of structural and functional changes in the nervous system. In particular, the aspects of the nervous system most commonly implicated are related to cognitive and emotional self-regulatory processing, language, and learning. However, the correlational nature of this evidence does not allow us to infer the causal mechanisms through which such relationships occur. To a large extent, the psychological significance of such associations will need to be elucidated in future research. However, the initial interpretation of the evidence –even in the neuroscientific field- has been in the sense of attribution of a poverty deficit (e.g., D´Angiulli et al., 2012). Recent studies indicate that the neural resources involved in arithmetic and reading processes vary depending on poverty in a qualitative sense and not according to which neural networks are activated or not during their solution (Demir-Lira et al., 2016; Gullick et al ., 2016). In these studies, it was found that children living in poverty conditions exhibited expected reading and arithmetic performance for their age and that at the neural level such performance was associated with the activation of different neural networks compared to those utilized by children not living in poverty. On the other hand, evidence has also begun to suggest that the neural resources involved in solving inhibitory control, attention control, and reading tasks may be modified by interventions in children from poor homes with and without developmental disorders (Neville et al., 2013; Pietto et al., 2018; Romeo et al., 2018).

Modulation for associations by individual and contextual factors

Since the end of the 20th century, research carried out in the context of education, developmental psychology, sociology, and pediatric epidemiology has allowed the identification of mediating and moderating factors of associations between child poverty, self-regulatory development, and mental health. Among the most frequently identified factors are perinatal exposure to infections, legal and illegal drugs, environmental toxins, or malnutrition; the physical and mental health status of children from birth; the state of self-regulatory, social, and language development of controls children; the number of prenatal checkups; the security of attachment bonds with parental figures (at least in societies with western cultures); different stressors in the contexts of child care and education; the quality of stimulation of learning at home and in child care centers; the mental health and lifestyles of parents, caregivers, and teachers; teacher training and pedagogical styles; access to social security systems through health, education, and social development policies; community resources; social mobility; social, political, and economic crises; cultural norms, values, and expectations, which may eventually induce exclusion phenomena such as discrimination or stigmatization; exposure to natural disasters or the consequences of climate change; and the time and duration of exposure to different types of early adversity (for reviews, see Bradley & Corwyn, 2002; Duncan et al., 2017; Hackman et al., 2010; Lipina, 2016; Yoshikawa et al., 2012).

In addition to the accumulation of potential risk factors, it is important to consider that poverty is a complex phenomenon that can co-occur with other types of adversities, such as orphanhood and consequent institutionalization, or exposure to domestic or community violence. In this sense, it is important to differentiate experiences due to lack of material resources from those characterized by the presence of threats to physical integrity (Sheridan & McLaughlin, 2014). The current consensus in developmental science is that the association between poverty and child development is modulated at least by the accumulation of risk factors, the co-occurrence of adversities, the susceptibility of each child to contextual factors, and the timing of exposure to adversities.

Contemporary neuroscientific studies of mediators and moderators of the association between poverty and neural development are also at a preliminary stage. The evidence to date has found that socioeconomic status moderates the association between neural structures and functions and self-regulatory performance; that neural structures and functions moderate the association between the socio-economic level and self-regulatory performance; and that different risk and protective factors mediate the association between socioeconomic status and structure and neural function (Farah, 2017; Lipina, 2016). This type of evidence has generated the hypothesis that two pathways whereby childhood poverty would influence neural development during the first two decades of life are the quality of parenting environments and the regulation of the stress response (Ursache & Noble, 2016). The latter would add to evidence accumulated since the middle of the 20th century that suggests that stress regulation is one of the most important mediators of the association between poverty and emotional, cognitive, and social development (Blair & Raver, 2016; Lupien et al., 2009).

Threats, negative life events, exposure to environmental hazards, family and community violence, family separations and moves, job loss or instability, and economic deprivation occur across the socioeconomic spectrum but tend to be more prevalent in conditions of poverty (Bradley & Corwyn , 2002; Maholmes & King, 2012; Yoshikawa, Aber & Beardslee, 2012). The neural systems associated with the regulation of such types of stressors include the hypothalamic pituitary adrenal (HPA) axis, the amygdala, and the prefrontal cortex, which together interact with immune and cardiovascular systems. These systems work together to regulate the physiological and behavioral responses to stressors, contributing to the adaptation processes of each individual to their contextual circumstances. In the short term, the activation of these systems serves as an adaptive biological response against stressors. However, under continuous or chronic stress, they may be associated with physiological deregulations with the potential to affect the cardiovascular and immunological health in the medium and long term (Dornela Godoy et al., 2017; McEwen & Gianaros, 2010; Robertson et al., 2015; Sandi & Haller, 2015).

Investigations of childhood poverty have begun to study the modulation of epigenetic mechanisms during early childhood development under different rearing and socioeconomic conditions, where experiences can alter the expression of DNA. For example, Essex and colleagues (2013) analyzed differences in adolescent DNA methylation as a function of reports of adversity experiences during their own childhood. The results indicated that the presence of maternal stressors in childhood and parental stressors in when children were preschool-aged predicted differential methylation effects. The results support the hypothesis that epigenetic changes would be involved at least partially in the long-term influences of early experiences (Gray et al., 2017). This suggests that understanding the role of the epigenome in behavioral modifications associated with early life experiences could contribute to understanding the relationships between childhood poverty and neural development. At present, the evidence does not allow us to infer causality in epigenetic relationships that have been established in the neuroscientific literature regarding the association between poverty and self-regulatory development.

Neuroscientific intervention studies with children living in poverty

A recent development in this area involves the use of research designs that combine neuroscientific techniques and intervention studies with controlled designs, aimed at optimizing cognitive and language performance in populations of children from poor households[5]. To date, only three such studies have been published. The first of these studies is the work of Neville and colleagues (2013), who developed an intervention, Parents and Children Making Connections – Highlighting Attention (PCMC-A), aimed at optimizing selective attention processes for preschool-aged children living in poverty in the city of Eugene, Oregon (United States), through the weekly implementation of two intervention components for eight weeks, at school, after school hours. One component of the intervention consisted of attention training activities for children through individual and small-group games. The other component consisted of two-hour meetings with parents and caregivers, during which they discussed parenting issues, stress management, and communication strategies for the home. To complement the activities with children, families were encouraged to conduct different activities at home in order to stimulate self-regulatory behaviors in children and to reduce stress-

[5] Neuroscientific intervention approaches aimed at analyzing levels of change (i.e., plasticity) of cognitive, language, and learning processes of populations of children with and without disorders, or early adversity problems not exclusively related to poverty (for example, maltreatment or institutionalization), began in the beginning of the last decade (Fisher et al., 2015; Lipina, 2016). This section only refers to those found exclusively with populations of children living in poor homes without identified disorders.

inducing factors in daily family communication. The researchers compared performance before and after the intervention, with that of children from the same context who participated in two other conditions (a similar intervention in which there was less emphasis on the parent training component and a business-as-usual condition with regular Head Start instruction and no additional intervention). Results showed that the children who participated in the PCMC-A program improved their cognitive performance at the behavioral level, but also at the neural level for a selective attention ERP component. Specifically, children who participated in the intervention expressed a neurophysiological pattern in which the activation of different neural resources could be differentiated for both relevant and irrelevant stimuli of the attention paradigm. The researchers also found that parents had reduced their perception of parenting stressors. In a later study, the same researchers also found that the children who benefited most from the intervention were those who had a specific polymorphism for a gene encoding serotonin transport (Isbell et al., 2018), adding evidence on the importance of considering different levels of organization, as well as the consideration of individual differences, in the impact analysis of the interventions.

The second of these studies corresponds to a computerized intervention designed by Romeo and colleagues (2018) for 6-9-year-old children with reading difficulties from different socioeconomic contexts, aimed at improving their performance in reading. After six weeks of fluency, spelling, and word reading training -implemented for four hours per day, Monday-Friday during the summer - the researchers found an increase in scores on standardized reading tasks and an increase in the thickness of neural networks involved in this type of processing (i.e., occipito-temporo-parietal), only in those children from lower SES homes.

The third of these studies was implemented by Pietto and colleagues (2018) and consisted of a computerized training aimed at optimizing cognitive control performance (i.e., inhibitory control, cognitive flexibility, working memory, planning) in 5-year-old children from lower SES homes. The training was implemented for 12 weeks, with 15-minute sessions weekly. Preliminary results showed an improvement in an ERP component related to inhibitory control processing only in the trained group.

Although in all three intervention studies described it is assumed that the implemented interventions are associated with the results, it has not yet been possible to identify which specific causal mechanisms are involved in the improvements. Consequently, the preliminary nature of these studies requires that their results be considered with caution while awaiting the replication or accumulation of more evidence on these types of studies. Currently, the importance of this preliminary evidence is that it is possible to support the hypothesis -already raised in interventions with samples of children with developmental disorders- that the efficiency of different neural systems can be modified by specific interventions; and that it is possible that this changes occur beyond the first two or three years of life.

Implications of the evidence, future directions, and contributions of this volume

The available neuroscientific evidence suggests that exposure to poverty is associated with structural and functional modifications of the nervous system, which in turn can be associated with lower performances on tasks with emotional, cognitive, language, and learning demands. Such associations can be mediated or moderated by different individual and contextual factors, among which individual susceptibility, the quality of parenting and educational experiences, as well as exposure to stressful negative events are among the most frequent. Finally, evidence has also begun to accumulate that suggests that such associations can be modified by interventions aimed at training cognitive control (i.e., attention, inhibitory control) and language (i.e., reading) processes, for at least the first decade of life. In summary, the evidence accumulated so far are consistent with the assumptions proposed by the RDS approaches: the associations of poverty with the neural and cognitive systems related to self-regulation and learning would not follow a fixed and immutable pattern due to exposure to deprivation.

This evidence may guide some actions, although not in sufficient detail to suggest specific policy practices in home, educational, or community contexts (Farah, 2018; Lipina, 2016), as can be verified with respect to the contributions in this regard from other disciplines (e.g., National Academies of Sciences, Engineering, and Medicine, 2019). On one hand, the available neuroscientific evidence could eventually complement that generated by other disciplines that address the problem of child poverty and the importance of early development, such as education and developmental psychology. On the other hand, the areas of nutrition, physical activity, sleep, and stress regulation could be those in which to concentrate research efforts to generate interdisciplinary collaborations that may address these issues. These four factors have been shown to be associated with self-regulatory development and learning, and they contribute to the increase or decrease of allostatic load and to learning (Beddington et al., 2008; Ribeiro et al., 2017).

Misconceptions about early critical or sensitive periods for self-regulation and learning, the interruption of development, or the acquisition of irreversible impairments from early exposure to poverty -notions that cannot be sustained with the available neuroscientific evidence- lead to representations of development as a much more fixed and less dynamic phenomenon than the empirical evidence supports. These misconceptions do not adequately consider the levels of plasticity and sensitivity to change in the context of a complex dynamic that involves phenomena not only biological, but also social and cultural.

The available evidence should be incorporated into debates on the contribution of scientific knowledge to social policies aimed at the care of children, adolescents, adults, and the elderly who do not have access to policies that guarantee their rights to health, education, and social development. This necessarily requires that we understand that policy design is a specific area of study of political science. Therefore, it is necessary to incorporate conceptual and methodological discussions in this regard, and this work constitutes a complex process that involves multiple actors and sectors with different interests, tensions, and disputes, which condition at the same time the processes of implementation and evaluation of interventions and policies. In this sense, the available neuroscientific evidence cannot be used to propose normative social objectives of adjustment and mismatch, either fixed or immutable. On the contrary, it contributes to the notion that poverty is associated with loss of rights and competences insofar as the wear and tear of the neural and physiological systems involved reduces opportunities for educational and social inclusion.

In the context of neuroscientific studies on poverty, researchers currently maintain as research objectives: (a) the elucidation of the psychological meaning of structural and functional neural variations; (b) the analysis of such neural differences in a qualitative sense, which contributes to identifying and differentiating adaptation processes (e.g., adaptation versus deficit); (c) the analysis of mediation and moderation dynamics between individual/contextual factors and different aspects of self-regulatory development, which in combination with intervention studies may eventually contribute to the identification of causal mechanisms of the association between poverty and neural development; (d) the identification of opportune moments during neural development to generate actions aimed at optimizing self-regulation development and learning processes; (e) the analysis of mutability and immutability processes by implementation and evaluation of studies with adequately controlled and longitudinal designs for their analysis; and (f) the generation of specific neuroscientific contributions that constitute an added value to that carried out by other disciplines.

Together, these research objectives could eventually contribute valuable evidence for the design and evaluation of specific practices and policies. This requires time, adequate financing –especially in those countries with insufficient resources or economic crises that reduce the possibilities of a continue scientific work, as is currently the case in South America-, and the generation of interdisciplinary and intersectoral collaborations with efficient planning and management. On the other hand, this type of effort necessarily requires the discussion of the implicit representations of human development that each sector supports, which would at the same time allow the updating of ethical, cultural, meta-theoretical, conceptual, and methodological notions, among others, that early childhood efforts today warrant and require.

Some of the aspects that such efforts could consider in the near future are: (a) the identification of specific targets and opportune moments for intervention in the areas of nutrition, physical exercise, sleep, and stress regulation in developmental contexts (i.e., home, school, community); (b) the multilateral financing of research projects aimed at generating large databases based on longitudinal collection of information on populations of interest and that include different levels of organization and developmental contexts; (c) the debate on the cultural relevance of conceptions, models, and designs for evaluation and intervention, in order to avoid or reduce the impact of the replication of standardized formulas in cultures foreign to those of implementation; (d) testing of technologies that permit the acquisition of data on the level of neural organization in developmental contexts (e.g., portable devices for EEG evaluation); and (e) the design of computational methods that include the consideration of information on the development of different levels of organization for the design and evaluation of interventions and policies.

The chapters included in this book provide evidence that raises hypotheses and reflections in line with the main questions in the area of poverty study from a neuroscientific perspective. Both the Rueda and Conejero chapter and the Demir-Lira chapter include initial sections devoted to correlational studies, which expand the available evidence on the associations between early living conditions, cognitive development, and academic performance at both the neural and behavioral levels. In the the Demir-Lira chapter, discussions also involve the importance of considering the opposition between deficit and activation when interpreting the results of neural studies with children living in poverty. The second part of this book includes four chapters that address different questions inherent to intervention efforts aimed at optimizing self-regulatory development and reading at the neural and cognitive level. First, Posner summarizes basic research efforts with animal and human models dedicated to identifying the neural mechanisms involved in intervention change. Pakulak and Stevens share an updated history of the research program carried out during the last decade at the Brain Development Lab of the

University of Oregon, which includes the design, implementation, evaluation, and cultural adaptation of a two-generation intervention. Romeo, Imhof, Bhatia, and Christodoulou update the evidence on an intervention program targeting reading. Such studies also contribute to the debate about the notions of the impacts of poverty as resulting in deficits versus promoting neural adaptation in the face of adversity, suggesting the need to explore variability in response to interventions. Carboni, Delgado, and Nin describe the design, implementation, and evaluation of a cognitive intervention program in the context of the Ceibal Plan in Uruguay. Finally, the third part of the book includes a series of chapters that propose different interdisciplinary explorations to address the analysis of mechanisms that can explain the associations between poverty, adversity, and neural development, as well as the scaling of correlational analysis and identification of mechanisms through different computational tools. These are the chapters of Perry, Thomas, Lomas, and Lopez-Rosenfeld and colleagues, respectively. Finally, Penn offers a series of reflections on the use of neuroscientific evidence in the Early Childhood Development sector, from the critical perspective of contemporary developmental psychology and sociology.

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PART I

Correlational Studies

3

EFECTS OF POVERTY ON EARLY NEUROCOGNITIVE DEVELOPMENT

M. Rosario Rueda and Ángela Conejero

Introduction: Neural plasticity and vulnerability

The question of to what extent the development of the individual's cognitive abilities is affected by the nurturing environment and experience has been essential in the study of human development throughout generations of researchers. In the field of cognitive neuroscience, the term *plasticity* is used to convey the idea that both the brain and cognitive abilities can change with experience.

As the brain is a plastic organ (Pascual-Leone, Amedi, Fregni & Merabet, 2005), it develops in connection with experience. Children's experiences nurture the brain and allow its optimal development. The degree to which the child's intellectual and emotional development is stimulated by their caregivers affects both the growth of the brain and functional effectiveness. The most plastic part of the brain, and therefore also the most vulnerable, is the one supporting the higher mental capacities of the human being, including language, attention, emotional and behavioral regulation, memory, and reasoning. A robust finding from psychological research is that these capacities are usually less optimal in children growing up in poverty. Similarly, school difficulties and behavioral problems are more frequent in children from families with lower socioeconomic (SES) levels (Bornstein & Bradley, 2003).

On the other hand, technological advances in recent years in neuroimaging have allowed us to study the associations between poverty and brain development. Neural networks associated with language, attention, and learning are particularly implicated in such associations (Hackman & Farah, 2009). These networks are developed to a lesser extent in children growing up in environments of greater poverty. A large body of data indicates that being raised by parents with a higher educational level fosters a child's language development (Hoff, 2006). The effect that parenting education has on a learned skill such as language is not a surprise. However, recent research shows that parents' SES also influences the development of other cognitive skills such as attention, memory, and intelligence. Furthermore, these investigations show that familial SES is also associated with the development of the brain regions in which these abilities are sustained (Noble et al, 2015). These cognitive functions are crucial for school learning, so their vulnerability to educational poverty or economic resources may partly explain the association between lower familial SES and lower school performance in children, which is reported consistently in the literature.

Early development of attention

During the second half of the first year of life, babies begin to develop their ability to control attention (Conejero & Rueda, 2017;

Rothbart, Sheese, Rueda, & Posner, 2011). For example, babies learn to direct their attention to a position on the scene where something interesting often appears before that object is presented. Moving attention to a place in anticipation of something interesting appearing is indicative that the baby, not the mere presence of the object, is the one who controls the attention. The development of attentional control in babies is associated with maturational changes that take place mostly in the anterior part of the brain, and specifically the frontal lobe. In the first two years of life, there is an exponential increase in the volume of gray matter and cortical thickness in this region of the brain, as well as the development of connections between neurons in this and other parts of the brain (Gilmore et al., 2012), and these changes will extend throughout childhood and much of adolescence.

Attentional control is the first step that allows us to regulate our behavior based on our own goals, rather than being at the mercy of external events or internal impulses that occur automatically. A good example of this is error detection. Many times, when our attention is monopolized by a thought or other activity, we make errors of action that we do not detect, or events around us go unnoticed. Therefore, attention is necessary to detect that something is wrong or happening in an unexpected way. Events that violate our expectations have been shown to arouse our curiosity and are of great importance in learning about the qualities of the world around us. Objects that behave in a strange way (e.g., a chick that barks instead of chirping) capture our attention more and arouse more curiosity to explore them than those that respond to expectations. In fact, a recent study has shown that even one-year-olds prefer to explore toys that have been seen to behave strangely over others that do the expected (Stahl & Feigenson, 2015). So, to the extent that we are able to detect these events, we will learn much more about the world around us.

Learning from mistakes: Brain response associated with mistakes

Besides attracting attention, or precisely because of it, unexpected events are recorded strongly in the brain. The brain response to errors has been widely studied by cognitive psychology since it was first characterized in the early 1990s (Gehring et al., 1993). Given the possibility of recording the electrical activity of the brain in a non-invasive way through electroencephalography equipment (i.e., electrodes placed on the surface of the head), it is possible to obtain a measure of brain activation with excellent temporal resolution. This allows very precise recording of when the brain responds to two conditions differently. In this way, brain activity in situations where an error is made can be contrasted with brain activity when the answer is given correctly. Through this technology we know that when an individual makes an error, a very characteristic activation occurs in the front of their brain, just about 100 milliseconds after giving the wrong answer, which does not happen after correct answers in the same task. This brain reaction is known as Error-Related Negativity (ERN), and is observed not only when the individual makes a mistake, but also when an individual notices a mistake made by another or observes something unexpected.

We can infer the likely activation source in the brain that produces the ERN signal recorded on the surface of the head through the use of mathematical models and other neuroimaging techniques. In this regard, it is proposed that the activation that gives rise to the ERN comes from the anterior cingulate gyrus, a region located in the front part of the brain that is of great importance for attentional control and learning (Dehaene, Posner,

& Tucker, 1994; Luu et al., 2003). In addition, the activation that gives rise to the ERN occurs at a specific neuronal firing frequency: between 4 and 8 Hz (4 and 8 firings per second); what is known as theta rhythm. Neurons from different parts of the brain that respond with the same rate of activation work in a coordinated and coherent way. Theta rhythm is the "language" that neurons use to communicate with others that also help in the task of detecting and learning from errors, a network of brain structures involved in the control and regulation of behavior (Cavanagh & Frank, 2014).

The study of the attention brain network functioning in babies

Drawing on this background on the brain's response to error detection, and knowing that the anterior cingulate cortex and the prefrontal cortex undergo accelerated development in the first years of life, in the Developmental Cognitive Neuroscience Lab at the University of Granada [Lab Neurociencia Cognitiva del Desarrollo] we have developed an experimental protocol that allows us to study the activation of the error detection system in babies. As mentioned above, this system is of crucial importance for attention and learning, so being able to study its operation in young children provides a tool to understand their early development and the possible environmental factors that can modulate (diminish or enhance) this development.

With this error detection protocol, we have carried out an investigation in which a total of 88 16-month-old babies initially participated (Conejero, Guerra, Abundis-Gutiérrez, & Rueda, 2016). In the first phase of the study, infants became familiar with three different types of simple puzzles that represented animal figures (chick, sheep, and monkey; see Figure 1). The first part of the familiarization phase consisted of a few minutes of experimenter-guided play in which each puzzle was completed with the actual pieces -always starting with the legs, following the body, and finally completing the puzzle with the piece of the head, after which the researcher named the animal represented by the puzzle (e.g., “it's a monkey!”). This process was repeated 3 times with each puzzle to create a representation of the correct construction of each figure. In the second part of the familiarization phase, the baby sat on his or her caregiver's lap looking at a computer screen presenting photographs of each puzzle completed on one side of the screen. On the other side of the screen, the figure gradually formed, presenting the animal's legs, body, and head drawn in black lines on a white background (color stripped image). To capture and maintain attention during the process, the presentation of each drawn part was accompanied by the characteristic sound of each animal and the animal's name when the figure was completed. After the familiarization phase, the experimental phase began. In this phase, babies watched the various puzzles with which they had previously become familiar. To do this, a flashy stimulus of color and a sound first captured the baby's attention. Once the baby was looking at the screen, the completion of a figure was presented, with the legs and body appearing first, and then the head, with the stipulation that in only a third of the tests the head was positioned correctly. In another third of the trials the last piece was placed wrongly (position error), and in the remaining third the head of a different animal was placed (conceptual error). Twelve trials were performed with each puzzle (4 of each condition: correct, position error, conceptual error), up to a total of 32 trials, and the type of trial that was presented was determined randomly by the computer.

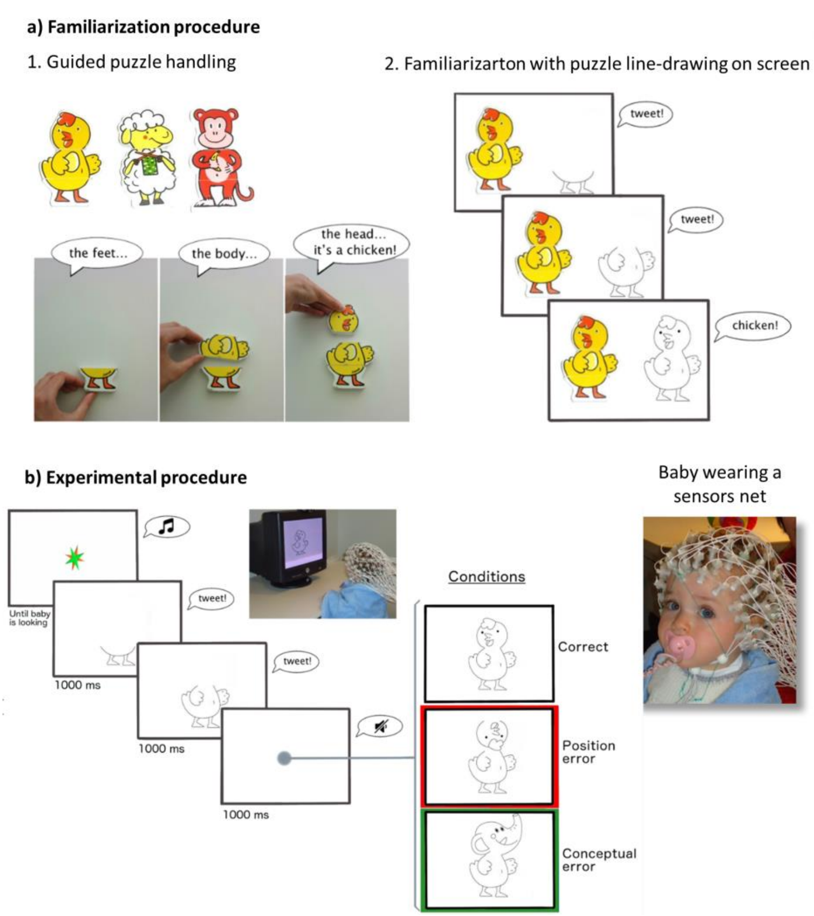

Figure 1 - Experimental procedures to characterize the brain response to the observation of errors in pre-verbal babies.

In order to record brain response to erroneous trials and to contrast it with trials in which the puzzle was completed correctly, infants were fitted with a sensor cap for electroencephalographic recording before beginning the experimental phase. In this way, we were able to observe that the brain presents a very marked activation in frontal regions, which occurs after observing both positional and conceptual errors (see Figure 2). However, this activation does not occur when the puzzle is completed correctly.

Interestingly, the brain response is practically identical in both types of errors. This is important because it indicates that this activation is specific to the error and is not influenced by the fact that the final piece is novel in trials with errors of conception, but not in trials with position error.

The first major finding of our study is the similarity in some aspects of the brain response to the error between infants and adults. The experimental protocol we have just described was also conducted with a group of 14 adults with a mean age of 22 years. Both infants and adults show more pronounced brain activation for incorrect completions compared to correct ones. Likewise, for both, the activation related to the error is mainly registered in the frontal sensors. Finally, when we analyze the rate of neuronal activation, we find that in both adults and babies there is greater activity in theta rhythm after observing errors. On the other hand, the main difference that we observe is that the brains of adults react much faster than that of babies. While the adult brain reacts differently to an error (compared to correct completion) at around 150 milliseconds after placing the last piece of the puzzle, babies take an average of approximately 450 milliseconds (see Figure 2). This was expected since the transmission of information in the brain of babies is much slower than that of adults, largely due to the still immature levels of axon myelination. The similarity between the brain reactions of 16-month-old babies to that of adults in the same task is important because it confirms that this experimental protocol, devised for pre-verbal babies, provides us with a marker of the activation of the brain's attentional system, which can help us to detect early alterations in the development of attention.

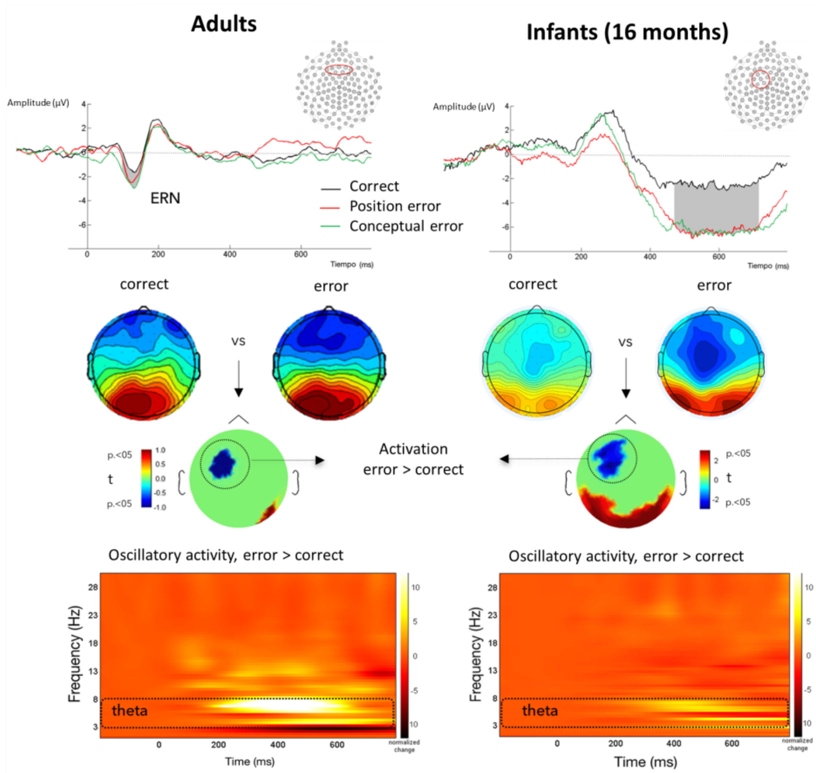

Figure 2 - Cerebral response to the observation of errors in adults and babies of 16 months.

The second major finding of our study involves the relationship between brain responses to an error in babies and their familial SES. The results show that there is a correlation between the family SES and the babies' brain processing during error detection (Figure 3). The familial SES is usually measured with three components: (1) parental level of education; (2) parental level of occupation; and (3) the level of family income according to needs (total income divided by the number of members of the family). The level of occupation in our sample of participants was estimated according to the 2011 National Classification of Occupations (RD 1591-2010, BOE 26 Nov 2010). The income level according to needs was calculated using the country's poverty threshold (according to the value provided by the Instituto Nacional Estadístico de España). Taking all three factors into account, we obtained a measure of SES for each family participating in our study. The results show us that the brain response to error differs substantially from one baby to another. While some babies show a clear difference in brain activation for incorrect trials versus correct trials, other babies show little difference. To examine the possible relationship between error-associated brain activation and familial SES, we performed simple regression statistical analyses that establish the relationship between two variables. These analyses show that familial SES is significantly associated with the amplitude of the brain reaction associated with the error shown by the babies. Specifically, according to the statistical regression model, 13% of the amplitude of brain activation to errors is explained by familial SES (see Figure 3). Of the three components that make up the SES measure, parents' level of education showed a positive correlation with the two brain markers of the error detection system: the amplitude of the brain response to error and the presence of activation in theta rhythm. However, occupational and income levels only correlated significantly with the amplitude of the brain response associated with the error. This result shows that the association between poverty and brain development can appear very early and, as such, the importance of alleviating educational and economic inequalities to favor the optimal development of children.

Correlation between infants' brain activation and family socioeconomic status indicators

	ERN amplitude	Theta activity
Parents occupation	.37**	n.s.
Parents education	.31*	.23*
Family Income	.24*	n.s.
Socioeconomic Status (SES)	**.35****	**n.s.**

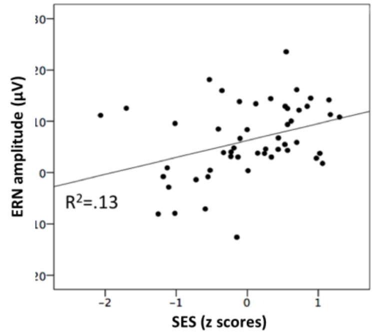

Figure 3 - Relationship between familial SES and the baby's brain response to the observation of errors.

Effects of poverty on the brain

Modern neuroimaging techniques, such as magnetic resonance imaging, allow the acquisition of high-resolution images of the brain and the quantification of the volume of brain mass, as well as the integrity and directionality of neuronal axons. Some previous studies that have used magnetic resonance imaging have shown that the frontal lobe in general and the anterior cingulate gyrus in particular, are structures that present a greater degree of vulnerability to familial SES factors. A study by Hanson and colleagues (Hanson et al., 2013) showed that children from poorer households have a lower growth curve of brain volume in the frontal (and also parietal) regions, compared with children raised in homes with higher SES. Despite starting at similar levels at age 5 months, children already show significant differences in frontal brain volume by 36 months of age based on their family SES (i.e., higher volume in children of families with higher SES). It has also been shown that there is a relationship between the thickness of the cerebral cortex in the anterior cingulate gyrus and familial SES. In this case, parental education is the factor that contributes the most to the statistical model that predicts the cortical thickness of this part of the brain at the end of childhood (Lawson et al., 2013).

However, data on factors related to poverty and the structural development of the brain are complex and in order to interpret them correctly, it is necessary to take into account the brain's maturational pattern throughout childhood and adolescence, as well as its relationship with cognitive abilities. In the first years of life there is a growth in the thickness of the cerebral cortex followed by a subsequent thinning that is marked at the end of childhood and during adolescence. Thinning of the cerebral cortex is a reflection of a shift to a more efficient brain function in which less useful neural connections are lost and axonal myelination is increased. There are neuroimaging data showing that the thinning process of the cerebral cortex is more pronounced in individuals with higher intelligence (Schnack et al., 2015). In this context, recent studies show that familial SES may be related to lower levels of cortical thinning, which in turn would be associated with less effectiveness in controlling attention and school learning in subjects such as vocabulary or reading (Brito et al., 2017). However, the measurement of cortical thickness or brain volume does not directly reflect the level of brain activation during task performance. In this sense, data from our study with infants show brain activation directly associated with error detection, and the results indicate that from the second year of life a significant relationship can be observed between family SES and the cerebral efficacy of the attention system involved in detecting errors.

The circle of poverty

Poverty can be represented as a circle of negative effects that prevent the individual from living with dignity and owning their future. The scarcity of resources has a direct impact on nutrition, access to education, health, and exposure to adverse situations and insecurity of various kinds. Also, in homes with fewer basic resources, greater health problems occur. There is also an increased risk of violence, with women being particularly vulnerable. Living in poverty has an impact on families' levels of stress, anxiety, and depression and has a profound effect on the affective and social relationships that exist between the members of the family itself, and also between these families and their social environment. Collateral to all these conditions, poverty puts the family at risk of social and labor marginalization, which in turn causes greater scarcity and adversity. In this way, the circle nurtures itself like a snowball (Figure 4).

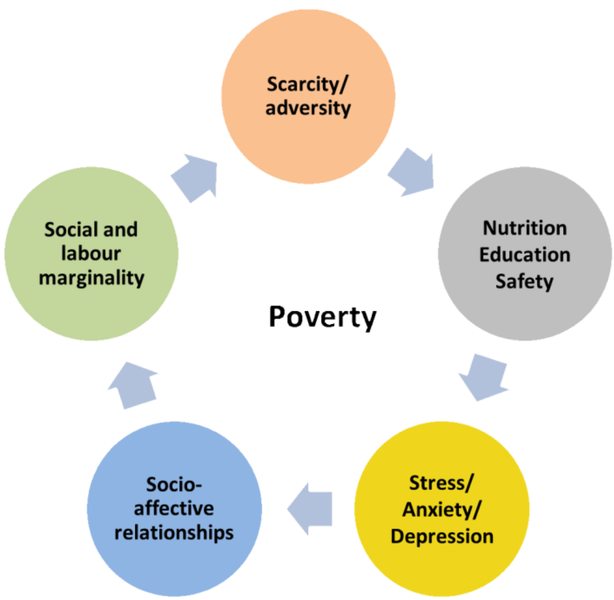

Figure 4 - The circle of poverty.

Research strongly suggests that the effects of poverty and not directly family income per se, are related to less optimal brain development. Furthermore, various research findings indicate that learning opportunities, including the use of consistent educational guidelines implemented effectively, are crucial and associated with better brain function (Bernier, Calkins, & Bell, 2016; Luby et al., 2016; Noble et al., 2015; Obradovic et al., 2010). Growing up in a safe environment rich in learning opportunities, as well as feeling loved and guided with sensitivity and affection, are the two aspects of the environment that seem to be most important for brain development. Unfortunately, poverty greatly affects caregivers' ability to provide these conditions for children.

Furthermore, the effects of the socioeconomic environment are observed from the first years of life. The brains of babies as young as one year old already show different functioning when babies are being raised in higher SES environments. This result is supported by previous research that showed early effects of the socioeconomic environment on the degree to which babies resolve situations that require executive control, such as the A-not-B task (Lipina, Martelli, Vuelta, & Colombo, 2005), as well as in the growth of the frontal region of the brain (Hanson et al., 2013).

Far from trying to stigmatize families with fewer economic and educational resources, these investigations attempt to deepen the knowledge of aspects related to poverty that may constitute factors of greater risk for the neurocognitive development of children. Some of the most studied factors are stress in the family, malnutrition, low levels of exposure to language, the physical and mental health of the caregivers, and misinformation about the cognitive development of children. These factors most likely decrease the quality of parent-child interactions and therefore affect the quantity and quality of information shared and children's learning opportunities. The ultimate goal of these studies is to identify risk and protective factors for development and report on them so that actions can be generated through actions and policies that eliminate or reduce educational and resource inequality between families, in pursuit of the optimal development of the child's cognitive abilities.

Relevance and implications

The different components of the SES measurement are associated with different aspects of children's cognitive development. While family income is more related to availability and access to resources, ranging from higher nutritional quality to better-endowed housing and neighborhoods, parental education is more associated with parents' educational style and cognitive stimulation strategies. Furthermore, families with higher levels of poverty are more likely to experience stress in their daily lives, and not only financially. These families often face housing that does not meet the necessary standards of well-being, as well as life in neighborhoods with higher levels of insecurity and less well-resourced schools. Similarly, families with fewer resources lack the means to invest in quality supplemental educational experiences for their children, and generally enjoy fewer hours than parents with higher economic levels to invest in family activities with educational value (e.g., attend theaters, concerts, parks, museums, among others). What the neuroscience data in this area suggest is that facing all these disadvantages is associated with alterations in the child's' cognitive and neural development in multiple ways. The study described in this chapter shows that already very early in development, some babies from poorer families show different levels of functioning in brain regions that have a crucial role in learning and the ability to regulate attention and behavior. This increases the likelihood that this early disadvantage, if left unchanged, will have an increasing impact as society and schools place greater demands on children's abilities to overcome their challenges.

Public policies to alliviate inequality: The role of education

Numerous studies indicate that there is a relationship between child poverty and the level of achievement in adult life. Data from a study published in 2010 in the United States show that children from families with incomes below the poverty line complete on average approximately two fewer years of formal education, compared to children from families with incomes two times the poverty threshold. Along the same lines, the income in the adult life of children from poor families may be less than half that of those from higher-income families. Vulnerability is also even higher for women, since girls from poor families are five times more likely to have a pregnancy outside of a stable relationship compared to girls raised in families with more resources (Duncan et al., 2010).

There are social reports that show the existence of a close relationship between the areas with the highest poverty rates and school difficulties and those with the highest levels of unemployment - a relationship that highlights the difficult job placement of young people with low levels of education (see the report *Iluminando el futuro: Invertir en educación es luchar contra la pobreza infantil* from Save the Children)[6]. More depressed neighborhood schools and educational districts often have less experienced teachers and more unstable educational teams, due to the high mobility of their members. This fact, in combination with the fact the educational challenges will undoubtedly be greater in classrooms with children with less attention span and self-regulation, has repercussions such that schools in neighborhoods with greater social difficulties must dedicate more class time to the

[6] https://www.savethechildren.es/publicaciones/iluminando-el-futuro-invertir-en-educacion-es-luchar-contra-la-pobreza-infantil

management of order and discipline and less time to learning content. This relationship could be eliminated or reduced through public policies that counteract educational inequality and make greater resources available to schools that suffer situations of greater risk.

These data emphasize the role of education in social inequality. The SES inequality of families can be perpetuated and even widened when SES segregation also occurs in schools. It has been shown that educational policies that promote educational segregation, such as support for private versus public education, or the promotion of competition between centers, through, for example, the publication of rankings of various kinds, can configure inequitable educational systems that threaten equal opportunities (Murillo & Martínez-Garrido, 2018). This type of data tells us about the social responsibility of states to alleviate the damaging effects of poverty and inequality through education, promoting the existence of inclusive schools. Education must be an instrument that generates equal opportunities and not a tool through which social inequality increases.

Cognitive intervention programs: Positive plasticity

The impact of family poverty and nurturing environments on babies' brain function is an example of brain plasticity. Just as negative experiences can adversely alter brain development, positive experiences can enhance brain development. Along these lines, a growing number of investigations in recent decades show that certain cognitive training strategies have positive effects on the functioning and structural development of the brain during childhood and adolescence, and also in adulthood (Strobach &

Karbach, 2016; Jolles & Crone, 2012)[7]. Much research remains to be done to establish to what extent cognitive training can alleviate inequalities related to SES and to identify the most effective intervention strategies and periods. However, the results of these investigations are promising and brain plasticity seems much higher than thought just a few decades ago. As professionals in psychology and cognitive neuroscience, it is part of our work to try to build knowledge that contributes to promoting the cognitive development of individuals, in the confidence that the prosperity and well-being of society will be greater as all members of society can optimally develop their mental abilities.

Conclusions

Poverty is not the same as simplicity and humility, nor can it be defined exclusively as the lack of economic resources. Emotional well-being and access to opportunities are not at odds with simplicity, but they are greatly affected by poverty. The brain develops best when it can do so under conditions of emotional well-being and access to basic educational resources. That poverty affects young children's brain development is not only unfair to children but also serves as a way to perpetuate poverty from one generation to the next. Neuroscience research puts new data on the table that we cannot ignore, and provides yet another reason to emphasize the need to fight inequality of opportunity. We want healthy, happy, educated, and resourceful parents and children for everyone!

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[7] See the following chapters in this volume: Carboni et al., Pakulak et al., and Romeo et al. (Editors' note).

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4

ACADEMIC RESILIENCE:

RELATIONS BETWEEN EARLY PARENTAL INPUT AND THE BEHAVIORAL AND NEUROCOGNITIVE BASIS OF CHILDREN'S ACADEMIC PERFORMANCE

Ö. Ece Demir-Lira

Introduction

Nations across the world spend millions of dollars on their children's education. Despite these efforts, however, millions of children fail to reach their learning potential. An overwhelming number of studies reveal that it is the children who come from economically disadvantaged backgrounds who are at a greater risk of falling behind (Bradley & Corwyn, 2002, Sirin, 2005). This gap between children who come from disadvantaged backgrounds and their peers from more advantaged backgrounds is referred to as the socioeconomic achievement gap (Reardon, 2011). The achievement gap is at the forefront of public discourse around the world as revealed via newspaper articles, books, and political commentary (Porter, 2002). The achievement gap in early school years also has strong implications for later life outcomes in adulthood, as early academic performance predicts high school graduation, college entrance, employment, and even health outcomes (Bradley & Corwyn, 2002; Brooks-Gunn & Duncan, 1997; Duncan et al., 2007).

Fields as diverse as psychology, neuroscience, sociology, economics, and education approach the achievement gap from multiple levels of analysis. Across these different fields, many scholars adopt a deficit model. Doing so has important implications for highlighting the possible equity problems present in the educational systems. However, not all children underperform. Despite their disadvantaged conditions, some children present favorable academic trajectories in school and beyond. The goal of the current chapter is to identify the sources of this academic resilience -the factors that counteract or moderate disadvantageous conditions and lead to academic success in children from diverse backgrounds. A rich body of literature examines the role of socio-affective factors in success. This literature focuses on constructs such as attitudes, motivations, and grit (Claro, Paunesku, & Dweck, 2016; Fuligni, 1997). Excellent reviews of this literature have been presented elsewhere (e.g. Ursache, Blair, & Raver, 2012). The current chapter, on the other hand, aims to examine cognitive factors that are associated with academic success - factors that might work to moderate or counteract disadvantageous effects of low socioeconomic status on academic performance.

From this perspective, we consider that to better understand why a child might succeed in the face of adversity, we ought to consider factors that surround the child on a more immediate timescale as well as the resources children might have developed in response to these experiences. In this respect, we examine factors one level up, at the parental level, and also one level down, at the neurocognitive level. Specifically, we will focus on two distinct but related factors that might predict children's academic success: the parental language input children receive at home and the neurocognitive systems children recruit when solving different academic tasks. We will argue that: 1) certain components of children's parental background might better predict academic outcomes than others, 2) the role of the environment will interact with children's characteristics, and that 3) parental background might differentially influence verbal versus visuospatial neurocognitive systems underlying academic performance. A better understanding the sources of academic resilience in young children will have implications for developing necessary supports for children in need before gaps in academic achievement emerge.

Why focus on parents? When discussing the role of parental background characteristics, the prior literature primarily relied on parental socioeconomic status (SES). Parental SES is a broad, composite construct. The discussions are still ongoing about measurement of SES (Enwistle & Astone, 1994; Lipina, 2007), but SES is typically assessed through multiple indicators such as parental education, income, and neighborhood or school indicators. Parental SES is only a distal measure of children's own approximate experiences in the home environment on a day to day basis. Focusing on the most active ingredient of children's daily environment might bring higher predictive power and shed further light on why some children fail while others succeed. Indeed, among multiple components of SES, parental cognitive stimulation might play the strongest role for children's academic outcomes (Brito & Noble, 2014). Specifically, parental language input strongly varies as function of parental background factors, such as SES, and strongly predicts children's language outcomes (Hart & Risley, 1995; Huttenlocher, Vasilyeva, Cymerman, &

Levine, 2002; Rowe, 2018). Below we argue that specific aspects of parental input might better predict children's academic outcomes than others and that these specific aspects of input might better predict outcomes than more broad indicators, such as parent income and education. Further, we suggest that not only the sheer quantity of parental input, but also the quality of the language input, matters for children's academic outcomes.

Why focus on the neurocognitive basis of academic performance? When discussing the achievement gap, the literature primarily focuses on standardized tests of performance. A standard score on a test reflects a composite outcome of multiple component processes. Although such measures reveal crucial information about individual's overall performance in a domain, they do not reveal the underlying systems that support a child's performance. Neuroimaging work has the potential to complement the behavioral work (e.g. Hoeft et al., 2007) and reveal how the neurocognitive systems children recruit as they are engaged in a task vary as a function of their parental characteristics. Here we argue that children from different backgrounds might recruit different networks in the brain to achieve academic success and perform at par with their peers.

To address the issues stated above, we will first review our work examining relations between parental input and children's behavioral academic outcomes. We will then discuss how parental input and parental background factors might also predict the neurocognitive networks children recruit during academic tasks. Specifically, the current chapter will present studies organized around three questions: 1) How does parental language input relate to children's language and literacy outcomes, 2) How does parental language input relate to neurocognitive basis of language processing? 3) How do parental background factors relate to neurocognitive basis of reading and arithmetic processing?

Parent language input and children's academic outcomes

Starting with the now classic study by Hart and Risley (Hart & Risley, 1995), a wide body of literature reveals that the parental language input children receive differs widely in quantity as a function of parental background. Further, it is now well-replicated that there is a relation between the quantity of the language input children receive and children's later language development (Hoff-Ginsberg & Shatz, 1982). While these results are very informative, they do not reveal a picture of the nature of the input children receive at home - or more specifically what are the different kinds of talk children hear that are associated with talk quantity. This is important because experimental studies show that children can and do learn new words based on a few, high quality experiences (Bloom, 2002; Carey & Bartlett, 1978).

Instead of focusing only on the input quantity, recent work started focusing on input quality- namely, specific aspects of parental language that might have the strongest relations to children's academic outcomes (Rowe, 2012). Building on this literature, in our work, we leveraged a longitudinal data corpus consisting of naturalistic parent-child interactions between child ages 1 to 5 years-old and measures of children's academic achievement in later years (Goldin-Meadow, Levine, Hedges, Huttenlocher, Raudenbush, & Small, 2014). Using these data, we examined academically-relevant aspects of input, including parental talk about letters, numbers, book-reading, and talk about abstract topics.

In one study, we focused on parents' talk about letters in everyday conversations, such as during playing with toys or eating. Talk about letters included a diverse set of utterances, including pointing out letters visually (e.g. "All of them are G's" - referring to letters in a television program) and spelling (e.g., "It begins with a P"). We found that parent talk about letters when children are 14 to 50 months-of-age predicted children's reading decoding outcomes at Kindergarten, even after accounting for parental SES and parental input quantity (Treiman, Schmidt, Decker, Robins, Levine, & Demir, 2015). Using the same dataset, in another study, we focused on parents' talk during naturally-occuring book-reading interactions. We showed that parental talk around books at child age 18 to 34 months predicted children's vocabulary, reading comprehension, and internal reading motivation as late as 3rd grade, controlling for other talk parents provide their children outside of book reading interactions, family socioeconomic status, and children's own early language skill (Demir-Lira, Applebaum, Goldin-Neadow, & Levine, 2018). We recently extended these relations to numerical development. Using the same longitudinal data, we identified the utterances that included a number token (e.g., "There is one airplane", "Look, four fish"). We found that parental talk about numbers at child age 14 to 30 months predict children's cardinal number knowledge at school entrance, controlling for parental input quantity and SES (Glenn, Demir-Lira, Gibson, Congdon, & Levine, 2018).

Finally, we focused on an aspect of parental language input that might best prepare children for the challenges of oral language in the classroom. Daily language use in face-to-face conversations is highly contextualized - the language is used to describe events, objects, and/or people that are present in the immediate environment. On the other hand, the language children are expected to produce and process once they reach school is highly decontextualized - this language is used to describe events, objects, and/or people that are not present in the immediate environment (Snow, 2010). Examples of decontextualized language include language used to give a presentation, language used in a history or a science text, or language used in a debate. Thus, decontextualized language is crucial for school success. Although decontextualized language use is rare in daily language, the roots of this language can be observed in some parent-child interactions early in life - when parents talk about events that happened in the past or will happen in the future, when parents engage in pretend play with their children, or when parents give their children explanations about cause-effect relations (Dickinson & Snow, 1987). Using the longitudinal data corpus discussed above, we examined how early parental decontextualized talk when children are 30 months of age predict children's later academic success. Decontextualized language input included talk about events that happened in the past or will happen in the future (e.g. "Mom is going to go to the foot doctor tomorrow"), talk during pretend play (e.g. "Come on horsies, gallop back to your stall"), and explanations (e.g. "Yes, let's turn the blocks so that you can see the patterns on them"). We focused on 30 months since this is a time period when parents first start talking about these abstract topics. We found that parent decontextualized talk predicted children's vocabulary, syntax, and narrative skill at Kindergarten and reading comprehension in 2nd grade. The relations remained significant even after controlling for parental SES, parent input quantity, and children's own language skill (Demir, Rowe, Heller, Goldin-Meadow & Levine, 2015). In recent work, we showed that early decontextualized language has far-reaching implications for academic language outcomes in midadolescence (Uccelli, Demir-Lira, Rowe, Levine & Goldin-Meadow, 2019).

This program of research showed that certain aspects of parental input might better predict children's outcomes than broad measures such as parental language input quantity, parent income or parent education. It is important to note that parental talk about letters, numbers, book-reading interactions and decontextualized talk are rare but rich aspects of parental language input. For example, only 7% of parents' utterances are decontextualized. However, there is considerable variability in the extent to which parents use these utterances. This is the variability that is significant in predicting later outcomes. Further, although such utterances are rare, they are richer than the rest of the talk in terms of linguistic complexity (Demir et al., 2015).

Such correlational findings are crucial in that they reveal the natural variability in parental language input and its implications for children's outcomes. However, many possible confounders might account for these relations. Some of these possible confounders are time-invariant confounders, such as parent education, familial income, child birth order, or child sex. Such confounders could be accounted for in typical regression analyses. However, there are also time-varying confounders - specifically the reciprocal relations between parents and children might contribute to the relations observed. In others words, early parental language input might predict children's language skill, which in turn might influence parental subsequent input. Future work will need to adapt causal models frequently used in other fields such as education or epidemiology to adjust for both kinds of confounders (e.g. Hong & Raudenbush, 2008). Our ongoing work using such models is also able to address questions about the timing of the input. We find that cumulative parental language input in preschool years, as opposed to input specific to early or late developmental periods, predicts children's vocabulary outcomes over and above time-varying and time-invariant variables (Silvey, Demir-Lira, Goldin-Meadow, & Raudenbush, under revision). Another central question to be explored in future work is why parents differ in their language input. Parents' knowledge about child development, parental beliefs and attitudes about child development, and parental views on parental contribution to child development are possible contributors (Kalil & DeLerie, 2004;

Rowe, 2008). In summary, specific aspects of parental language input predict children's academic outcomes, even after controlling for parental SES and child factors.

Parental background characteristics and the neurocognitive bases of children's academic performance

Environmental effects on the brain are now well established both in animal studies as well as adult training studies (e.g. Kemperman, Kuhn, & Gage, 1997; Voss, Vivar, Kramer, van Praag, 2013). In children, a growing body of literature highlights the relations between parental SES and the networks in the brain that support academic performance (Brito & Noble, 2014; Hackman & Farah, 2009; Lipina & Colombo, 2009). This literature also suggests that SES might have stronger relations to verbal systems in the brain than visuospatial systems (Farah et al., 2006). However, the existing literature primarily focuses on the relations between broad parental background factors, such as SES, and static features of brain structures, such as cortical thickness or white matter structure. Less is known how the systems children recruit as they are engaged in different academic tasks vary as a function of parental characteristics (Raizada, Richards, Meltzoff & Kuhl, 2008). Similarly, not much is known about the role of children's immediate experiences, such as parental language input. In recent work, we asked how early parental input children receive relates to the neurocognitive systems children recruit in school years for an academically-relevant task, specifically narrative processing. Prior literature suggests that narrative processing recruits verbal-semantic networks, including middle temporal areas, as well as visuospatial networks, including bilateral parietal areas in the brain (Mar, 2004; Szaflarski, Altaye, et al., 2012). We asked if as a function of their parental language input, children recruit similar systems but to varying extents or different systems in the brain.

To address this question, we focused on the sample included in the longitudinal study described above. We administered a passive narrative processing task in the scanner, where children were asked to watch a storyteller telling different stories. The task was administered to a subsample of the children participating in the longitudinal study when children were 8-10 years old. We then examined how the neural networks that underlie narrative processing covary with early parental decontextualized input children received in preschool years -the same decontextualized input measure leveraged in our prior work (Demir et al., 2015). We found that parental decontextualized input children received in preschool years was positively correlated with greater activity in bilateral superior/middle temporal gyri during narrative processing. On the other hand, a network that consisted of bilateral superior/inferior parietal, premotor, and angular gyrus was negatively correlated with decontextualized input. Importantly, parental decontextualized input was not significantly related to children's behavioral performance on the post-scan questionnaire they were administered about the stories they heard (Demir-Lira, Asaridou, Goldin-Meadow, & Small, 2016). These findings suggest that children with rich linguistic experience in earlier years might recruit areas that have been implicated in semantic processing in narrative processing, whereas children who are exposed to this input to a lesser extent might rely on visuo-spatial model building and spatial imagery. Overall, this study highlights that children might recruit different networks in the brain as a function of their early life experiences even when they perform the same behaviorally.

In our recent work, we examined if these differential patterns extend beyond language processing to later-developing academic skills such as arithmetic processing and reading. Arithmetic processing recruits a wide network in the brain including verbal systems in the fronto-temporal areas and visuospatial systems in the parietal areas (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999; Prado, Mutreja, & Booth, 2014; Venkatraman, Ansari, & Chee, 2005). Mirroring our study on narrative processing, we asked if, as a function of their parental characteristics, children recruit similar systems in the brain but to different extents or different systems in the brain. In the context of these studies, we did not have access to parental language input. Thus, children's parental background was assessed by parental education. We focused on the average education level of both parents because parental education is more stable than income or occupation, is closely related to parent–child interactions and home learning environment, and is considered to be a stronger predictor of academic achievement than income and occupation (Duncan & Magnuson, 2012; Lewis & Mayes, 2012).

In this study, children were asked to solve single-digit subtraction problems in the scanner. Independent localizer tasks were used to identify verbal and visuospatial networks in the brain. Regression analyses were used to examine areas in the brain that show increases or decreases in activation as a function of parental education. In addition, a measure of children's math skill was also included in the model to see if children from varying backgrounds recruit different systems as a function of their skill level. We found that for children with higher parental education, the higher the children's math skill, the higher was the activation in left middle temporal areas, identified by the verbal localizer. At lower SES levels, higher skill was associated with greater recruitment of right parietal cortex, identified by the visuo-spatial localizer (Demir, Prado, & Booth, 2015).

In another study, we found that these differential activation patterns predicted future skill growth in math. For children at the higher end of the SES continuum, reliance on verbal networks, specifically left inferior frontal areas, predicted skill growth over up to 3 years. For children at the lower end of the SES continuum, however, reliance on visuospatial networks in right parietal areas predicted growth over the same time period (Demir-Lira, Prado, & Booth, 2016). We recently reported that these differential relations are not limited to functional activation patterns. Differential patterns also extend to structural differences associated with reading skill. Our work examining relations between parental socioeconomic status (SES) and white matter tracts suggested that children with higher SES and higher skill might recruit tracts that are associated with orthographic skill to a greater extent than children with lower SES. Children with lower SES but higher skill might rely on supplementary tracts underlying visuospatial processing more than higher SES peers (Gullick, Demir-Lira, & Booth, 2016). Overall, these results suggest that across different tasks including language processing, reading and mathematics, children from different backgrounds might recruit different networks in the brain to perform at par with their peers.

What are the implications of the different activation patterns according to parental background? How do we interpret the findings above? On the one hand, these differences might indicate delays. Both our work and prior work shows that children from disadvantaged backgrounds experience lower quantity and quality of language input. It might be that children who have richer experiences with linguistic stimuli early on rely on symbolic, verbal systems when processing narratives, when reading and even when solving basic arithmetic problems. Children who are not as familiar with rich language information might instead recruit visuospatial networks and mental model building for support in a variety of tasks. Supporting this view, Romeo and colleagues showed that children who experience richer conversational interactions exhibit greater left inferior frontal activation during narrative processing than their peers who experience such conversations to a lesser extent (Romeo, Leonard, et al., 2018). Over time with experience, even the latter group might shift to recruiting visuospatial systems to a lesser extent and switch to verbal systems. Indeed, the literature on expertise suggests that in any domain as individuals gain experience, they might shift from depictive models to abstract, symbolic representations (Raghubar, Barnes, & Hecht, 2010; Schwartz & Black, 1996). At the neurocognitive level, this transition is reflected in from reliance on visuospatial networks to verbal networks.

However, an alternative interpretation is possible. These patterns might indicate adaptations. Children might be adapting to their environment, and recruiting different systems to achieve success depending on their unique experiences. Specifically, children who come from disadvantaged backgrounds might develop alternative strategies to achieve success. Especially on tasks with no significant differences in children's behavioral performance as a function of parental background, as it is the case in our studies, differences at the neurocognitive level might reflect different strategies. Rather than a one-size-fits all approach, these different profiles might have implications for the individualized learning environments developed to support children. For example, future work is needed to examine whether children from disadvantaged backgrounds might indeed benefit from visuospatial supports to a greater extent than their peers from more advantaged backgrounds. Importantly, these two explanations are not mutually exclusive. While early on children from disadvantaged backgrounds might recruit visuospatial systems and might benefit from visuospatial supports, the systems they recruit might vary and change as they get older, as they gain richer experience in and outside of school and as they are faced with different, more challenging tasks. Such questions will be addressed by future studies examining developmental trajectories of children using analysis at multiple-levels, ranging from neurocognitive measures to studies focusing on environmental experiences. Promising findings on the effects of family-based interventions on child brain and behavior is emerging (Neville, Stevens, Pakulak, Bell, Fanning, Klein, & Isbell, 2013). Future work should continue to explore the effects of interventions on the neurocognitive networks underlying academic performance.

Conclusions

To summarize, the body of work presented in this chapter attempts to examine why it is that certain children, often from disadvantaged backgrounds, fall behind when their peers thrive at school. One perspective to take in examining this question is to focus on academic resilience; to identify factors that predict success in children from diverse set of backgrounds. Two of these factors we focused on are parental input children receive at home and the neurocognitive systems they recruit in different academic tasks.

Our findings to date suggest that parental background influences on children's academic outcomes are specific, reciprocal, and non-uniform. Relations are specific in that certain aspects of parental input might better predict children's academic outcomes than others. The majority of the prior literature focused on the quantity of the parental language input, which forms the basis of many interventions in the field. However, our work suggests that constrained, rich parent-child interactions might also support children's outcomes. Relations are reciprocal in that influence of parental input vary as a function of child characteristics. The neuroimaging work presented above suggest that children adapt different strategies in different environments to perform at par with each other. Overall, the characteristics that children bring into the learning environment and how the environment responds to these contribute to children's academic resilience. Emerging statistical models support efforts to examine reciprocal and cascading interactions between parents and children. Finally, relations are non-uniform in that verbal versus visuospatial neurocognitive systems might be differentially influenced by parental environmental characteristics. Across a wide range of tasks and measures, we observed that children from more advantaged backgrounds might recruit verbal systems to a greater extent to achieve success, whereas their peers from more disadvantaged backgrounds might recruit visuospatial, analog systems to perform at par with their peers. Thus, these findings suggest that children recruit different systems as a function of parental factors and this contributes to their academic resilience.

The findings covered in this chapter raise new questions for future work. Our work focuses on performance on basic academic tasks, such as single-word reading or single-digit arithmetic. Going forward, future work should examine children's performance on academic tasks that present specific challenges in later years in school, such as solving math word problems or reading connected texts. Do children continue to recruit different networks as a function of their parental background or are there limitations to the adaptations children present? On the other hand, it is crucial to examine when do these differences emerge. When do children start recruiting different networks in the brain? How do these differences develop over time?

Overall, the research program presented above reveals complex relations between parental background factors and children's academic performance. Our findings show that these relations can only be fully understood by tracking children's developmental trajectories starting from early preschool years, examining the effect of multiple, dynamically interacting factors on child's development at each stage in time, which in turn have direct and indirect effects downstream. This requires an approach that examines child development at multiple levels of analysis including neurocognitive and environmental using multiple methods such as neuroimaging and behavioral naturalistic observations and working with children with a wide range of skill levels. Our hope is that by understanding the protective factors that promote academic resilience in children from different backgrounds, we will be in a better position to effectively and successfully promote academic success of all of our children.

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PART II

Intervencions

5

MECHANISMS OF BRAIN TRAINING

Michael I. Posner

Introduction

In our work we have suggested two basic methods of brain training (Tang & Posner, 2009; 2014). Network training involves practice on a cognitive task such as the Flanker, Stroop, or N Back, etc. These tasks are rather simple but they are involved in school skills such as learning to read or compute. It is generally agreed that performance on the trained task will improve with practice, and improvement may be fit by a power function or an exponential function (Anderson, 1982; Heathcoat, Brown & Mewhort, 2000). For this form of training it is reasonable to ask about transfer to similar or remote tasks. Many school subjects would involve attention network or working memory and thus may improve because both the cognitive task and school subject involve common networks.

A second form of training involves changing the brain state in a way which influences many networks. Physical exercise and meditation have been two widely studied ways to change brain state. Tang (Tang et al., 2007) developed a meditation method called Integrated Body Mind Training (IBMT). It is a form of mindfulness meditation, and the findings we have made with IBMT we expect would be true of many forms of meditation training. Since state training does not involve a specific cognitive task it is reasonable to ask what range of tasks might be improved by the training, but this would not strictly speaking be transfer.

The term brain training suggests that the training modifies specific brain structures. If details of how brain structures could be modified by training were better known we might have an improved chance of understanding the similarities and differences between network and state training and be in a position to understand the possibility of transfer or the range of tasks induced by the state change.

One of the forms of state training involves mindfulness meditation. We used IBMT as a way of modifying brain state (Tang et al., 2007). We selected a large group of undergraduates at the University of Oregon and in China and randomly assigned them either to meditation or a relaxation training control. They spent five days for one half hour per day in the assigned training. Before and after training they were tested with the Attention Network Test (ANT), gave a subjective judgment of mood, and were tested for cortisol following a challenge with mental arithmetic. We found the meditation group showed significantly better executive attention, higher positive mood scores and lower negative ones, and were less stressed following the mental arithmetic than the relaxation controls.

In our later studies (Tang et al., 2010, 2012) we found that Fractional Anisotropy (FA), a measure of the efficiency of connections, was increased following 2-4 weeks of IBMT in comparison with the relaxation training control. Figure 1 shows the chief brain pathways for which FA was increased significantly more following IBMT than or controls. After two weeks Axial Diffusivity (AD) was improved (AD is thought to be related to axonal density), while after four weeks both AD and RD were improved (RD is thought to be related to increased myelination). These changes occurred in pathways surrounding the Anterior Cingulate Cortex (ACC) as shown in Figure 1.

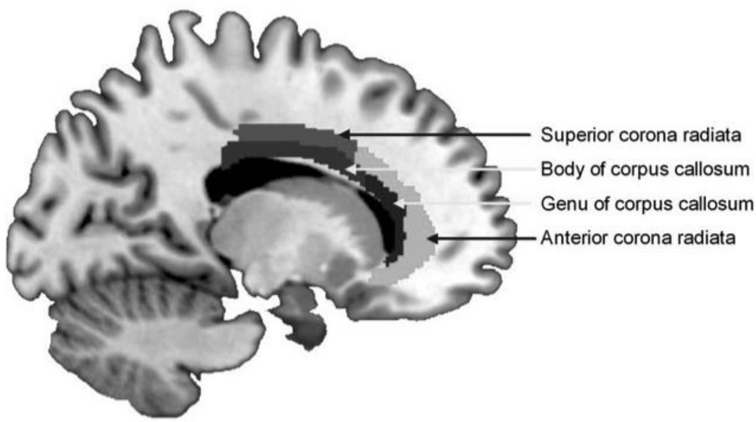

Figure 1 - Brain networks surrounding the anterior cingulate are increased in connectivity following meditation training.

How might a purely mental practice like IBMT produce a change in white matter? At the time we began our mouse studies it was surprising that white matter should change in adults following practice. Many people including me believed that the cells that changed myelination were active in childhood but not in adults. However, after careful reading of the literature, I found evidence that during demyelinating diseases like multiple sclerosis dormant oligodendrocytes could become active and produce myelin (Beirowski, 2013). We speculated that the theta rhythm increased in frontal areas after meditation training (Xue et al., 2014) might also serve as a means of activating dormant cells (Posner, Tang &

Lynch, 2014). In the last few years many human and animal studies have shown improvements in white matter with various forms of network and state training (McKenzie et al., 2014; Wang & Young, 2014).

Mouse studies

To test this idea we used a mouse model; we implanted lasers in mice who had been genetically bred to increase output of cells in the ACC with pulses of light (Piscopo et al., 2018; Weible et al., 2017). Figure 2 shows the design and areas of implantation in the mouse anterior cingulate.

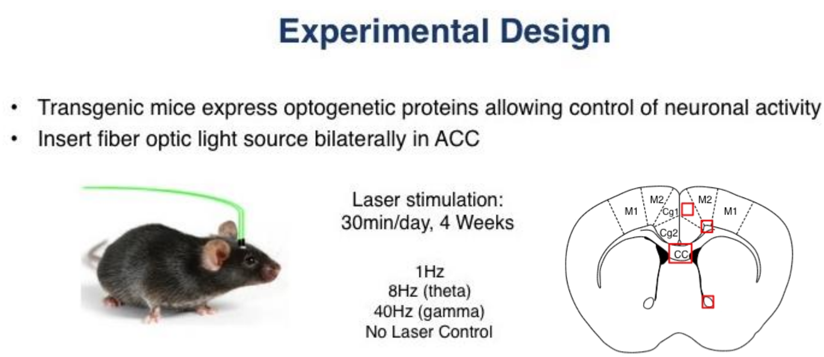

Figure 2 - Areas in the mouse brain in which lasers were planted to activate cells in the anterior cingulate (ACC), the test sites in the cospus callosum (CC), and the control sites (no laser control) in the anterior commissure.

We found that when the output of the ACC was increased by rhythmic stimulation in the range of 1-8 Hz there was an increase in oligodendrocytes (the cells that myelinate axons). However, this effect was primarily due to 1Hz not 8 Hz stimulation. We also created electron-micrographs magnified 16,000 times, from 10 mice, 6 had received low frequency (1 or 8

Hz stimulation) for a month ½ hour per day and 4 were unstimulated controls. Figure 3 shows a single axon surrounded by rings of myelin.

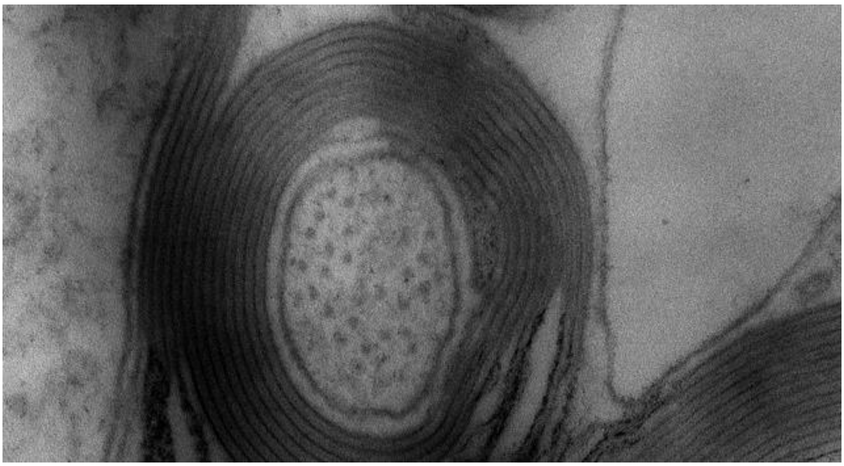

Figure 3 - The central part of this figure is a single axon, the rings surrounding the axon are the myelin (white matter) which helps to improve connectivity (the figure taken from an electron microscope is magnified 16,000 times).

We compared the g ratio (axonal diameter/axonal diameter + myelin) measured from the EMs in stimulated versus unstimulated mice**.** We found the ratio was similar to those usually reported from the central nervous system of mice for the unstimulated controls (Gibson et al., 2014) and was significantly reduced in the stimulated mice. The reduction in g was the same in both 1 and 8 stimulated groups, although the number of observations was too small to test this difference formally. Usually, a reduced g ratio is associated with increased myelin. In our case it was due to a combination of increased myelin diameter and reduced axonal diameter. We do not think our reduced axonal diameter is an artifact of including lower diameter fibers for the stimulated mice, but we are unable to satisfactorily explain the reduced diameter. A review of efforts to remyelinate fibers in the corpus callosum (Franklin & Frech-Constant, 2017) concluded that they generally produced thinner myelination of small fibers and thus increased the g ratio, so the effect of stimulation may be stronger than changes actually found in g indicate.

We also found a behavioral effect of low stimulation particularly in the 8 Hz group. We found that time spent in the light when given a choice between light and dark areas of the cage was increased in those mice in the low stimulation group compared to unstimulated controls (Weible et al., 2017). Choice of the light is usually taken as a sign of reduced anxiety and/or increased exploration. The size of these behavioral effects are greater the smaller the g ratio (Piscopo et al., 2018).

Human studies

It is a goal of our work to determine if low frequency stimulation can lead to improved connectivity in the human brain. Since our study began with effects of meditation on the human brain and since other forms of learning have also shown improvements, why would we need to carry out these studies? The reason is that white matter exists throughout the human brain while meditation and other methods only produce changes within the particular pathways stimulated by that learning method. Moreover, we do not know if the changes in white matter would improve in groups of people subject to white matter abnormalities such as the aged, those with multiple sclerosis, closed head injury, or other degenerative disorders, or if improved connectivity would increase learning more generally.

We have approached our work in three phases. Only Phase 1 is currently complete. Phase 1 is to determine if there is a method for none or minimally invasive stimulation to increase theta range stimulation in the ACC. We compared groups given 6Hz auditory input, neurofeedback on their current theta activity in the ACC and given low levels of electrical stimulation of the ACC at 6 Hz from scalp electrodes as shown in Figure 4.

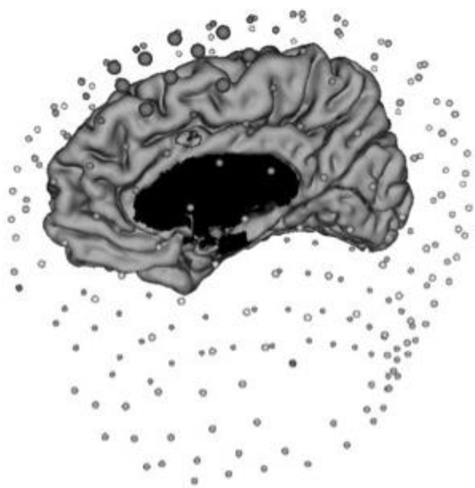

Figure 4 - The dots indicate the location of electrodes on the scalp. The larger dots are those used to insert electrical activity into the brain. The dorsal ACC is the brain area receiving the strongest electrical input, although other areas are also stimulated.

Each of the groups was tested with and without a task that also stimulated the ACC. We found that electrical stimulation while performing the Attention Network Test (ANT) was effective in producing increased theta during a non-stimulation period following one minute of stimulation. Figure 5 and 6 illustrate the theta activity over each electrode site for a single participant for the baseline when no stimulation was present (Figure 5) and for the minute following electrical stimulation when the person was performing the ANT (Figure 6). Overall, we found a significant increase in theta over midline central electrodes when using electrical stimulation while performing the ANT but not in the other conditions.

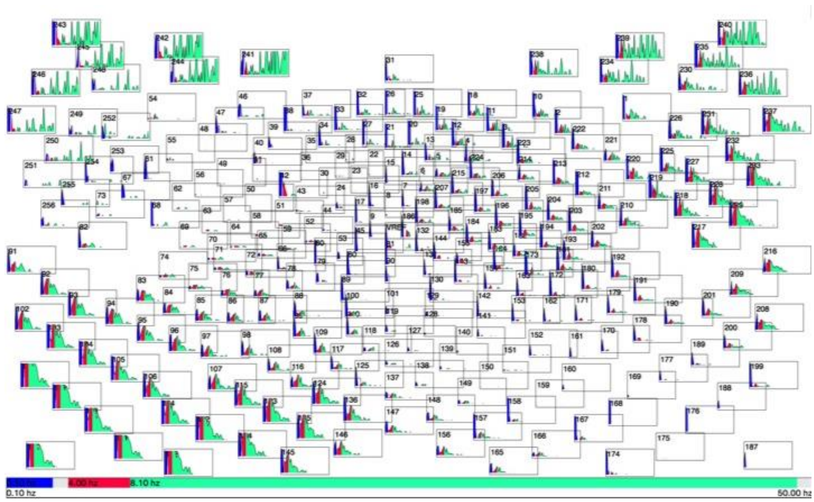

Figure 5 - For each electrode site the red rectangle represents the theta rhythm at that electrode. This figure is for the baseline period of one electrical subject. There is relatively little theta activity present in midline electrodes related to ACC.

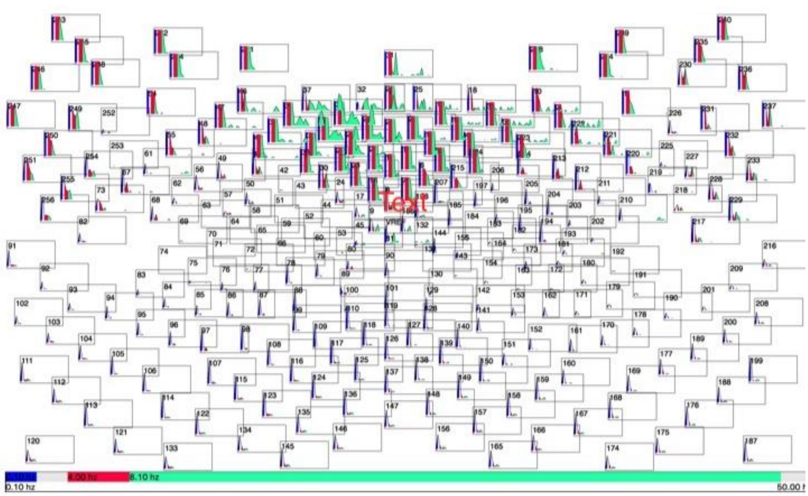

Figure 6 - This figure is the same participant as the previous figure and shows the theta activity (red) at each electrode site. The figure is for the minute following electrical stimulation while the person is performing the ANT. In this condition theta over central electrode sites is very strong.

In phase 2 we will compare the generic electrodes used in the study cited above, which are the same for each participant, as shown in Figure 4, with individual electrodes based upon a structural MRI of each participant's brain to choose optimal scalp stimulation sites. We will also examine activation of the ACC during the ANT with a task that activates the motor system. To activate the motor system we use a serial RT task (Curran & Keele, 1993; Grafton, Hazeltine & Ivry, 1992). This experiment may allow us to choose the best electrodes for stimulation and generalize our approach to brain areas other than the ACC. In our view nearly any area of the human brain can receive strong activation by scalp electrodes, especially when guided by structural MRI. Cognitive psychologists certainly have developed tasks that also can be used to activate at least many of the possible target brain areas.

In our third phase we plan to use Diffusion Tensor Imaging before and after a month of electrical stimulation together with an appropriate cognitive task to determine whether any change in white matter occurs. We hope to see changes in fractional anisotropy (FA) following the electrical stimulation to the cingulate plus ANT in comparison with an un-stimulated control group.

A number of mostly neurological disorders such as closed head injury, stroke, or multiple sclerosis are known to be caused, at least in part, by abnormalities in white matter. However, many other psychiatric conditions such as autism, attention deficit disorder, and addiction produce disordered brain networks that might rest upon white matter abnormalities. For example, studies of tobacco addiction have shown that meditation produces both a change in white matter and a reduction of smoking (Tang, Tang & Posner, 2013). These changes occur, irrespective of whether the person intended to quit smoking or not (Tang, Rothbart, Posner & Volkow, 2014). We believe that the meditation works through frontal theta to improve connectivity between the ACC and striatum, which is deficient in smokers, and the restored connectivity reduces craving and thus smoking.

Brain training and transfer

If further experiments show we can alter white matter anywhere in the brain with electrical stimulation plus an appropriately designed task, an important step will be to determine if improving brain connectivity is a realistic way to improve learning in relevant school subjects.

The brain networks that underlie skills such as reading, calculating, and writing are being understood (Dehaene, 2010, 2011). There is little question that specific and often mostly non-overlapping brain networks underlie a variety of skills that are constituents of intelligent behavior. At the same time, there is also little doubt that a variety of tests of intelligence are correlated across domains (Duncan et al., 2000). These correlations support the idea of a general intelligence mechanisms (g). The specific mechanisms that underlie "g" still remain to be established. Two prominent possibilities are: (1) multipurpose brain areas such as those underlying attention (Crittenden, Mitchell & Duncan, 2016) and (2) molecular mechanisms that underlie common mechanisms of learning (Voelker, Rothbart, & Posner, 2016). These are not mutually exclusive and both mechanisms could be involved. We have discussed in this paper our effort to improve one common network, namely the executive attention network (often called cingulo-opercular in the imaging literature; Dessenbach et al., 2007). Below we consider new findings concerning the second possibility.

Methylation

Much interest in the education community is in differences in the rate at which people learn skills. In order to design education to maximize human potential it is necessary to know what causes poorer learning and what can be done to remedy such difficulties.

One can reasonably ask whether knowing something about the neurobiology of brain changes during learning can do anything to help us in this worthy goal. One real advantage of the network approach to cognition is that individual differences can be seen rather naturally as being dependent upon the efficiency and plasticity of the underlying networks.

We have previously shown that individual differences in the efficiency of performing conflict tasks are related to differences among genes related to the neuromodulators dopamine and serotonin (Fan, Fossella, Summer, Wu & Posner, 2003; Gree, Munafo, DeYoung, Fossella, Fan & Gray; 2008; Posner, Rothbart, Sheese & Voelker, 2014). Performance by adults in a serial reaction time task that measures implicit and explicit learning (Curran & Keele, 1998) is related to the MTFHR polymorphism that influences the efficiency of methylation (Voelker, Rothbart & Posner, 2016). We find that in children this same polymorphism is related to the change with learning of the brain network carrying out conflict tasks (Voelker, Rothbart & Posner, 2017). Since conflict tasks are a marker of executive attention it follows that people with more efficient methylation would develop improved self-control more rapidly. We don't believe that the MTHFR gene is unique in its relation to intelligence, but only that it is one of probably many genes which are related to intelligence.

Why does methylation influence the rate of learning of new skills in children and their performance in adults? One role of methylation is to vary the rate at which myelin is added to brain networks. If, as we have argued in this paper, myelination changes are associated with learning in both rodents and humans, it follows that those with more efficient methylation will learn faster. In this view, rate of learning at least for those skills related to myelination will itself be subject to genetic variation.

Of course learning a single skill like how to read or compute may have vast influences on overall school performance. Most of our knowledge comes through listening and reading, thus these two skills can influence much of what is learned in school. Moreover, both reading and listening depend in part on attention.

There is little question that specific and often mostly non-overlapping brain networks underlie a variety of skills that are constituents of intelligent behavior. We need a high priority for research at both the neural system and molecular levels to understand how these networks support intelligent behavior in all domains. We may hope that this research will lead to a better understanding of how to foster transfer between specific learning in school subjects and more general intelligent behavior in other domains. As we await further investigation of these mechanisms hopefully there are insights from both separate brain networks and a common g factor that can be applied to foster better achievement in educational settings.

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6

APPLYING NEUROSCIENCE RESEARCH TO INTERVENTIONS ADDRESSING POVERTY

Eric Pakulak and Courtney Stevens

Introduction

It is fair to ask what value cognitive neuroscience has for the study of relationships between socioeconomic background and later life outcomes. Does the addition of neuroscience simply provide another outcome measure on which differences can be demonstrated between those from higher and lower socioeconomic backgrounds? More dangerously, does such research turn attention away from the structural features that create inequality in the first place, thereby distracting from a focus on the underlying factors that generate the conditions for inequality? While these are certainly valid concerns and possible outcomes, we argue that the careful use of neuroscience data provides valuable insight into the mechanisms whereby inequality becomes biologically embedded and associated with a wide and disparate range of life outcomes (e.g., McEwen &

Gianaros, 2010; Nusslock & Miller, 2016; Pakulak, Stevens, & Neville, 2018; Ursache & Noble, 2016). The focus on neurobiological substrates does not deny or take away from the larger structural issues at play (e.g., see McEwen & McEwen, 2017 for discussion of structural issues), but a neurobiological lens does provide a unique window for understanding the complex embedding of socioeconomic status and inequality. This research can also guide the development and evaluation of programs designed to improve outcomes for those in poverty. A greater understanding of mechanisms can both identify powerful levers that can be targeted by intervention programs, as well as provide more proximal outcome measures that can be incorporated into assessment practice.

In this chapter, we situate the review of a program of research applying cognitive neuroscience to the study of socioeconomic disparities into a larger framework that interrogates the value – both real and potential – of such research. This work takes as its starting point a robust literature linking socioeconomic status (SES) with a wide and disparate range of distal outcomes. These outcomes, which in many cases widen across development and extend into adulthood, include school grades, high school graduation rates, physical and mental morbidity, as well as mortality (e.g., Lipina & Posner, 2012; McEwen & Gianaros, 2010; Nusslock & Miller, 2016; Pakulak et al., 2018; Ursache & Noble, 2016). While these relationships have been well-known for decades, models in cognitive neuroscience seek to elucidate the intermediate pathways by which aspects of the environment are associated with changes in behavioral performance and health outcomes, as well as differences in brain structure and/or function.

Here, we focus on two pathways that have been characterized as primary mechanisms linking socioeconomic background to differences in later life outcomes. These include (1) the home linguistic environment, which can impact language and literacy outcomes as well as brain function for language, and (2) chronic stress exposure, which can impact the development of attention and self-regulation skills as well as the brain network supporting these skills (e.g., Ursache & Noble, 2016; Pakulak et al., 2018) Evidence on these neural systems and related pathways, and in particular the neuroplasticity of selective attention, has informed a series of studies moving from basic research on the effects of selective attention on neural processing to intervention research examining the malleability of these processes in young children from lower socioeconomic backgrounds.

In the sections below, we begin by briefly reviewing socioeconomic disparities related to these two key outcomes (language and attention / self-regulation), as well as aspects of the caregiving environment related to both outcomes. Next, we describe the evolution of a research program that has moved from basic research on the neuroplasticity of selective attention to the development, implementation, and evaluation of a two-generation intervention. This intervention includes work with both preschool children in poverty and their parents/caregivers. The intervention highlights the role of the caregiving environment to influence both the linguistic environment as well as family stress and self-regulation in children. By targeting both key pathways in part via the caregiving environment, this intervention has been demonstrated to result in positive changes in children from lower SES backgrounds across a wide range of outcome measures, including a neural index of selective attention, as well as to lead to positive changes in parents. Finally, we describe the cultural adaptation of this intervention for use by Spanish-speaking families in the United States and Colombia, as well as a larger project in which we have developed a delivery model of the intervention for larger-scale implementation by non-research staff.

This larger-scale implementation model further targets stress reduction by increasing the degree of consistency between the classroom and the home environment. We end with a consideration of what questions in the field should be prioritized in the coming decade, as well as the professional value of interdisciplinary interactions among researchers examining these questions as different levels of analysis.

Socioeconomic disparities and key pathways

Childhood socioeconomic disadvantage can have a lasting legacy, as evidenced by the strikingly wide range of later negative life outcomes predicted by lower socioeconomic status early in development (for more extensive reviews, see e.g., Hackman, Farah, & Meaney, 2010; Lipina & Posner, 2012; McEwen & Gianaros, 2010; Pakulak et al., 2018; Ursache & Noble, 2016). While there is variability across individuals, a child growing up in poverty is more likely, for example, to experience a range of mental and physical health problems through adulthood and can also expect to die younger (e.g., McEwen Gianaros, 2010; Nusslock & Miller, 2016). Early socioeconomic disadvantage is also associated with poorer academic grades, standardized test scores, and graduation rates (e.g., Bradbury, Corak, Waldfogel, & Washbrook, 2015; Sirin, 2005) Undoubtedly, these differences in outcomes reflect equifinality, with a number of factors that co-occur with early socioeconomic disadvantage- and factors that often interact with one another- contributing to differences in life outcomes. These include but are not limited to variation in school quality, neighborhood safety, nutrition, and health care access (e.g., McEwen & Gianaros, 2010; McEwen & McEwen, 2017). However, emerging theories point to a set of integrated biological systems that are affected by early adversity and might underlie many of the diverse outcomes associated with early socioeconomic disadvantage (e.g., Lipina & Posner, 2012; McEwen & Gianaros, 2010; Nusslock & Miller, 2016; Pakulak et al., 2018; Ursache & Noble, 2016). The study of these neurobiological systems, and in particular how aspects of the environment can shape their development, can provide insight into the mechanisms whereby early socioeconomic disadvantage becomes biologically embedded and ultimately impacts such a wide and heterogeneous range of outcome measures.

Understanding which neurobiological systems are most sensitive to early adversity, as well as the environmental factors that influence their development, is one way of 'pulling back the curtain' on a complex set of relationships. At the same time, it is important to note that identifying particular environmental factors that mediate the relationship between socioeconomic status and later outcomes is not meant to serve as a reductionist approach to understanding poverty. Instead, this approach can identify specific pathways that might serve as individual levers within larger efforts to address poverty. By this view, such research has the potential to provide immediate and evidence-based approaches implementable at multiple levels of society, from the home environment to public policy that can impact schools, neighborhoods, and communities. While such approaches are not intended as complete anecdotes to the pernicious effects of socioeconomic disadvantage, approaches that target foundational neurobiological systems at important points in development have the potential to provide positive support and serve as buffers to these effects on child development.

Here, we highlight two core systems, language and attention/self-regulation, that have been the focus of much research in cognitive neuroscience generally, as well as studies specific to poverty and early disadvantage (e.g., Hackman & Farah, 2008; Hackman et al., 2010; Noble, Norman, & Farah, 2005; Ursache & Noble, 2016). Although we and others often discuss different pathways by which early experience affects language versus attention / self-regulation (Brito & Noble, 2014; Noble, Houston, Kan, & Sowell, 2012), it is important to note that there is some overlap in and interaction between pathways (e.g., Ursache & Noble, 2016), such that strategies that target one pathway may ultimately benefit multiple outcome domains (Stevens & Pakulak, in press).

Language

There are large and growing gaps in academic achievement as a function of SES (e.g., Bradbury et al., 2015). Differences in language and literacy skills have been hypothesized as one key cognitive disparity underlying overall achievement gaps, either as a result of limited language skills or a mismatch between the language skills of children from lower SES backgrounds and the skills required to succeed in school (e.g., Hoff, 2013). Neural systems supporting language, and in particular those supporting phonology and grammar, display great neuroplasticity early in development (Stevens & Neville, 2014) and as such are sensitive to differences in early experience associated with adversity but also, as discussed below, malleable with intervention.

Early adversity has long been associated with poorer language outcomes (for more extensive reviews, see e.g., Perkins, Finegood, & Swain, 2013; Ursache & Noble, 2016). A groundbreaking study by Hart and Risley (1995) showed socioeconomic differences in both the *amount* and the *nature* of language input heard by children as well as in rates of vocabulary growth. Children growing up in less affluent homes were more likely to hear directives, yes/no questions, and criticism, and also showed slower vocabulary growth between ages one and three than children from professional families. This pattern has been replicated for vocabulary acquisition (Hoff, 2003) and extended to the acquisition of complex syntax (Huttenlocher, Vasilyeva, Cymerman, & Levine, 2002); in both studies parental language input accounted for these differences in language acquisition. Data from the latter study showed a similar association between teacher language input and children's syntactic development, suggesting these differences operate at least in part through environmental exposure.

Differences in language skills as a function of SES emerge before the beginning of formal schooling and widen across the school years (Bradbury et al., 2015). Recent work by Fernald and colleagues has further found that SES predicts both vocabulary and word processing efficiency at 18 months of age, as well as the trajectory of these abilities, such that children from lower SES backgrounds are estimated to be six months behind their peers from higher SES backgrounds in word processing efficiency by 24 months of age (Fernald, Marchman, & Weisleder, 2013). As well, there is some evidence to suggest that among cognitive systems, language outcomes are particularly vulnerable. For example, studies that have included assessment of multiple cognitive systems suggest the largest effects of SES are observed in language outcomes relative to other systems (Farah et al., 2006; Noble, McCandliss, & Farah, 2007; Noble, Norman, & Farah, 2005). However, with these studies it is important to note that assessments of language systems generally use established measures with known strong psychometric properties (e.g., high reliability), which may render these tests more sensitive to group differences in language outcomes than those of other cognitive systems.

Socioeconomic status has also been shown to account for variability in the structure and function of neural systems important for language in both children and adults. Structurally, five-year old children exhibit differences in gray and white matter volume in left inferior frontal gyrus (LIFG), an area of the brain that mediates aspects of semantic, syntactic, and phonological processing, as a function of SES (Raizada, Richards, Meltzoff, & Kuhl, 2008). The same study found that SES predicted left hemisphere functional specificity for phonological awareness, an important skill for reading development. SES also predicts regional volume in left inferior frontal and superior temporal gyri, and there is evidence that these SES differences increase with age (Noble et al., 2012). A recent study further found that SES was associated with reduced cortical surface area in multiple neural regions, including inferior frontal gyrus bilaterally (Noble et al., 2015). In adults, neighborhood-level socioeconomic deprivation predicts the degree of cortical thinning in bilateral posterior perisylvian language areas (Krishnadas et al., 2013), and retrospective childhood SES predicts proficiency on behavioral measures of language proficiency as well as the early neural response to syntax over left frontal brain areas in adult monolinguals from a wide range of SES backgrounds (Pakulak & Neville, 2010).

While correlational evidence such as that described above should be interpreted with caution, taken together, these findings suggest that well-documented disparities in language development associated with early adversity emerge early and may endure into adulthood. Given the importance of language skills for general academic achievement, this also suggests that language may be a foundational skill that could be targeted early in development. In addition, the important role of the linguistic environment provided by caregivers suggests that this pathway is a possible lever for targeting language disparities. As discussed below, evidence that both parent language input and child language skills are malleable with intervention further supports this characterization.

Attention/self-regulation

The second key outcome implicated in prior cognitive neuroscience research on socioeconomic disparities is attention/self-regulation. As complex constructs, attention and self-regulation include a number of component processes. For example, models of attention generally recognize the importance of a basic level of arousal and focused selection of specific stimuli for further processing, which includes both enhancing selected signals (signal enhancement) and suppressing irrelevant information (distractor suppression). Self-regulation is defined as primarily volitional regulation of attention, emotion, and executive function for the purposes of goal-directed actions (Blair & Raver, 2012, Blair & Raver, 2015). Executive functions subsume a diverse set of psychological processes, including inhibitory control, working memory, and cognitive flexibility (e.g., Diamond, 2006; Diamond, 2013). Importantly, attention and self-regulation are foundational systems for learning across domains (Blair & Raver, 2015; Stevens & Bavelier, 2012) and also display relatively greater plasticity compared to other neural systems (Stevens & Neville, 2014). Though beyond the scope of the present chapter, it is also important to note that an integrated neural network underlying attention and self-regulation – including the prefrontal cortex (PFC), hippocampus, and amygdala – is also crucial to many aspects of health and immune system function, and thus may link more broadly to the diverse range of outcomes associated with early socioeconomic adversity (e.g., Nusslock & Miller, 2016; Pakulak et al., 2018).

As with measures of language described above, behavioral measures of attention and self-regulation also show differences as a function of socioeconomic background that emerge early and are evident into adulthood. Often these studies have examined specific subskills considered part of attention and self-regulation, such as inhibitory control, attention shifting, response inhibition, and working memory (Blair et al., 2011; Farah et al., 2006; Mezzacappa, 2004; Noble, McCandliss, & Farah, 2007; Noble et al., 2005; Sarsour et al., 2011). These disparities are evident across the lifespan, emerging in infancy (Lipina, Martelli, Vuelta, & Colombo, 2005) and also documented throughout childhood (Noble et al., 2007; Noble et al., 2005) and into adulthood (Evans & Schamberg, 2009). In addition, the amount of time a child spends in poverty early in development predicts performance on executive function tasks at age four, suggesting a gradient relationship between poverty exposure and outcomes in development (Raver, Blair, & Willoughby, 2013). Moreover, studies that have examined or reviewed multiple outcome cognitive domains suggest that in some cases, along with language, attention and self-regulation systems show the greatest socioeconomic disparities (e.g., Hackman et al., 2010; Noble et al., 2005; Ursache & Noble, 2016).

A growing body of evidence suggests that socioeconomic status also accounts for differences in the structure and function of neural systems important for attention and self-regulation. Socioeconomic adversity is associated with structural differences in the PFC (Noble et al., 2015; Noble et al., 2012; Raizada et al., 2008), amygdala (Luby et al., 2013; Noble et al., 2012), and hippocampus (for extensive review, see Brito & Noble, 2014; Hanson, Chandra, Wolfe, & Pollak, 2011; Jenkins, Belanger, Connally, Boals, & Durón, 2011; Noble et al., 2015; Noble et al., 2012). Further neuroimaging evidence suggests that differences in socioeconomic status are also associated with differences in functional activation and connectivity among these regions. For example, a recent study of 7-12 year-old children found that early adversity was associated with reduced negative connectivity between the PFC and both the amygdala and hippocampus, suggesting reduced top-down control of these regions in children from lower SES backgrounds (Barch et al., 2016). Early SES disparities have also been associated with poorer performance and greater PFC activation in a novel rule learning task, suggesting that early adversity may result in less efficient PFC function (Sheridan, Sarsour, Jutte, D'Esposito, & Boyce, 2012). As well, a recent electrophysiological study indicates that lower SES is associated with reduced error-related negativity and frontal theta in toddlers, which are believed to index the function of aspects of executive function involving the prefrontal cortex and anterior cingulate (Conejero, Guerra, Abundis-Guitiérrez, & Rueda, 2018).

Consistent with a larger body of research with animal models, a growing body of research in humans suggests that a relationship with a sensitive and nurturing caregiver can potentially buffer the effects of early adversity on these foundational regulatory systems (e.g., Stevens & Pakulak, in press). In particular, parental sensitivity and responsiveness are important for the development of a secure attachment relationship, which is in turn important for the development of neurobiological systems supporting regulatory function (e.g., Gunnar, Brodersen, Nachmias, Buss, & Rigatuso, 1996). A retrospective study found that high caregiver nurturance early in development provides a buffer against the long-term health problems associated with early adversity (Miller, Chen, & Parker, 2011). However, multiple aspects of environments associated with socioeconomic adversity increase the amount of stress experienced by parents, which has been found to reduce the likelihood of sensitive maternal child care and the development of secure attachments, which in turn increases the likelihood of stressful interactions with caregivers (e.g., Blair & Raver, 2012; Meaney, 2010). Evidence also suggests that caregiving is associated with structural differences in the brain systems discussed above, as parental nurturance at age four predicts hippocampal volume in adolescents from lower SES backgrounds (Rao et al., 2010) and caregiver support mediates the effects of early adversity on the structure of the hippocampus (Luby et al., 2013).

Taken together, these data suggest that, as with measures of language, outcomes related to attention and self-regulation show differences as a function of socioeconomic background. Also, like language, attention and self-regulation are sensitive to differences in caregiving and have been hypothesized to serve as foundational skills, with the potential to influence processing across a range of domains and predictive of academic success (Blair & Raver, 2015; Stevens & Bavelier, 2012). Below, we describe work from the Brain Development Lab (BDL) that evolved from a focus on the plasticity of neural systems for selective attention to intervention research examining the malleability of these systems in children from lower socioeconomic backgrounds.

From basic to translational research

Neuroplasticity of selective attention

For the past 15 years, we have been part of large research program in the BDL with a focus on the development and plasticity of selective attention (for reviews, see Isbell et al., 2017; Stevens & Neville, 2014). The term 'selective attention' refers to the ability to select and preferentially process specific information in the environment while simultaneously suppressing the processing of irrelevant, competing distractors, and thus requires many subskills that are part of attention and self-regulation (e.g., inhibitory control, distractor suppression, signal enhancement). We have emphasized selective attention because it is a skill that has the potential to impact functioning across a range of domains. In this respect, we consider selective attention to act as a "force multiplier" that can have broad-reaching impacts on different aspects of cognition. In support of this, performance on selective attention tasks has been linked both to academic skills in general (e.g., Stevens & Bavelier, 2012) and to specific cognitive abilities, including speech segmentation, working memory, and nonverbal intelligence (e.g., Astheimer & Sanders, 2012; Giuliano, Karns, Neville, & Hillyard, 2014; Isbell, Wray, & Neville, 2016).

Using a child-friendly ERP paradigm, we have been able to document that typically developing children as young as three years of age can modulate neural processing with selective attention (Coch, Sanders, & Neville, 2005; Sanders, Stevens, Coch, & Neville, 2006). In these studies, attentional modulation of neural responses was apparent within 100 msec of processing, suggesting that children – like adults – showed relatively early effects of selective attention on neural processing. However, we later observed that some groups of children did not show these same robust effects of selective attention on neural processing. This included children with specific language impairment or with low pre-literacy skills (Stevens et al., 2013; Stevens, Sanders, & Neville, 2006).

However, our most striking findings were differences in the effects of selective attention on neural processing as a function of children's socioeconomic backgrounds. In both preschool (Giuliano et al., in press; Hampton Wray et al., 2017) and early childhood (Stevens, Lauinger, & Neville, 2009) samples, we found that lower SES was associated with reduced or absent effects of selective attention on early neural processing. Independently, a separate research group demonstrated similar SES disparities in an adolescent sample (D'Angiulli, Herdman, Stapells, & Hertzman, 2008). Moreover, these electrophysiology studies permitted a degree of specificity about mechanisms: in all cases, socioeconomic differences in selective attention were specific to reduced suppression of distracting information in the environment, as opposed to enhancing task-relevant information (D'Angiulli et al., 2008; Giuliano et al., in press; Hampton Wray et al., 2017; Stevens, Fanning, & Neville, 2009).

At the same time, we had evidence suggesting that these neural mechanisms were modifiable, with enhancements of the effects of selective attention on neural processing possible in some circumstances. For example, individuals born congenitally deaf or blind exhibited larger effects of selective attention in the remaining modalities (Neville & Lawson, 1987; Röder et al., 1999). Likewise, we found that when children received intensive language or literacy instruction that effectively improved the targeted skill, we also observed increases in the effects of selective attention on neural processing (Stevens, Fanning, Coch, Sanders, & Neville, 2008; Stevens et al., 2013). This raised the hypothesis that we might be able to develop interventions that targeted selective attention directly, rather than tangentially, and in ways that harnessed some of the pathways described earlier linking early adversity to language and attention / regulation outcomes. However, this work was undertaken recognizing that the goal was not necessarily to 'remediate a deficient system' but rather to support children in deploying a skill that may be particularly important in classroom environments. Indeed, reduced suppression of environmental information might be adaptive in more chaotic environments associated with early adversity, but maladaptive in a classroom environment (Blair & Raver, 2012; Blair & Raver, 2015). As discussed below, these observations led to hypotheses concerning the training of these foundational systems.

Development of an evidence-based intervention

The work described above, and in particular our basic research on selective attention, led us to consider interventions that could target attention and self-regulation specifically. While not intended as a panacea, we hypothesized that targeting these foundational systems at a key point in the development of the neural networks supporting these skills might yield large gains, possibly across multiple domains. Together with educators and a large team of researchers (Neville et al., 2008; Neville et al., 2013), we worked to develop an evidence-based intervention that could target these key pathways in children from lower SES backgrounds.

Research on the importance of caregiving and the home environment suggested that working directly with parents would be a powerful way to target multiple key pathways, specifically those both related to the linguistic environment as well as family stress. This was informed by the seminal work of Phil Fisher and colleagues at the Oregon Social Learning Center (OSLC), who showed that a parenting intervention targeting family stress regulation via strategies supporting positive reinforcement, consistent discipline, and monitoring of child behavioral states and activities reduced stress in foster parents and normalized diurnal cortisol patterns in foster children (Fisher, Gunnar, Chamberlain, & Reid, 2000; Fisher & Stoolmiller, 2008; Fisher, Stoolmiller, Gunnar, & Burraston, 2007).

A series of pilot studies working with local Head Start partners resulted in the development of a two-generation intervention that involved simultaneously working with parents and children. Children received small-group training in activities aimed at improving attention, self-regulation, and stress regulation. The intervention also included working with parents to modify the caregiving environment by encouraging them to monitor and change their language use with children and to reduce stress by improving consistency and predictability. The parent component was adapted in part from OSLC work (Fanning, 2007; Reid, Eddy, Fetrow, & Stoolmiller, 1999) and consisted of procedures encouraging family protective factors and strategies targeting family stress regulation, contingency-based discipline, parental language use and interactive responsiveness, and facilitation of child attention. The parent component also made explicit links to the child training exercises. These exercises, developed in a series of pilot studies (Neville et al., 2008), featured small-group activities designed to improve the regulation of attention and emotion states as described in more detail below. This also presented an opportunity to directly compare two different delivery models of this two-generation approach, which differed in the relative balance of child- versus parent-focused training. While both models included both a parent- and child-component, we compared a model that included relatively more time working with parents (and thus likely influencing the caregiving environment) versus a model that involved more time with child-directed activities but less time working directly with parents. Given the role of the home environment on the pathways being targeted, we predicted that the more parent-focused model would yield the greatest gains.

The initial evaluation study included an eight-week delivery of these two models as well as a passive control group that received Head Start with no additional programming (Neville et al., 2013). Pre-/post- change scores from multiple outcome domains were compared across groups. We targeted typically developing, monolingual children (N= 141) and their parents/guardians/ caregivers (hereafter "parents"), all of whom were participants in Head Start and living at or below the national poverty line. Families were randomly assigned to one of three groups: the more parent-focused model, the more child-focused model, or Head Start alone. Results across multiple outcome domains favored the more parent-focused model, Parents and Children Making Connections – Highlighting Attention (PCMC-A), and revealed positive changes in targeted pathways and systems. We found changes in the caregiving environment related to both language and stress. We also found improvements in parent's verbal turn taking with their children, an aspect of language behavior that predicts good language development. Parents who received PCMC-A also reported reductions in parenting stress, suggesting that two-generation interventions have the potential to change the caregiving environment in ways that may benefit children and also parents themselves.

Using parental self-report measures, we also documented reductions in child problem behaviors and improvements in social skills. We also found that children randomly assigned to receive PCMC-A showed significantly greater improvements in receptive language and non-verbal IQ than children in either comparison group. Perhaps most strikingly, children randomly assigned to PCMC-A also showed improvements in brain function for selective attention such that after the eight-week program their brain function for selective attention looked more like that of their higher SES peers (Figure 1). Thus we documented changes both in key pathways by which early adversity is hypothesized to affect the development of systems important for language and attention/self-regulation, as well as behavioral and neurophysiological improvements in these systems.

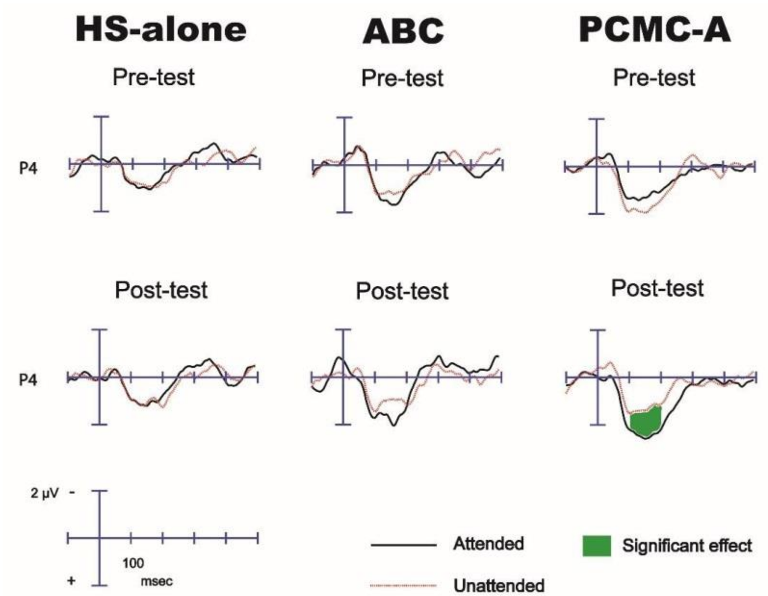

Figure 1 - Significantly greater increases in the brain function for selective attention (100-200 ms) in children in the PCMC-A group compared to Head Start alone and the child-focused delivery model (Attention Boost for Children, ABC) in representative waveforms from centro-parietal electrode P4 (reprinted from Neville et al., 2013).

The work above provides one example of the application of neuroscience to an intervention. This line of research applied both the findings and tools of cognitive neuroscience to an intervention study focused on families facing socioeconomic adversity. The focus on multiple aspects of language, parenting stress, and brain function for selective attention was informed by research from cognitive neuroscience suggesting that these neurobiological systems are particularly sensitive to environmental differences associated with early adversity and mediated by key pathways associated with caregiving. Therefore, we consistently emphasized the importance of caregiving to the developing brain. In addition, we incorporated some evidence from cognitive neuroscience into parent training materials. For example, we included a brief discussion of the roles of the amygdala and hippocampus to help parents understand what their child may be experiencing during periods of emotional saturation. Anecdotally, we found that parents responded well to what they often described as a more concrete understanding of their child's developing brain as well as how their actions affect this development. In discussions about the brain, we also emphasized the exquisite plasticity of the developing brain, in particular for the language and regulatory systems that were often the focus of strategies being presented, discussed, and practiced in role-play activities.

Evidence from cognitive neuroscience also informed specific training approaches. To take one example from the child component, given the research described above on the mechanisms of selective attention we collaborated with an experienced educator to develop engaging activities that would simultaneously train signal enhancement and distractor suppression. These activities involved having one child perform an attention demanding task, such as walking a weaving line while balancing a plastic ball in a spoon, while other children actively provided visual and auditory distractions (with all children rotating through both roles). This activity was scaffolded over the eight-week program such that the distracting elements intensified in a step-wise fashion, for example by having the "distractors" move physically closer and use increasingly distracting activities each week.

Finally, our direct assessment of brain function for selective attention provided a more proximal outcome measure believed to be foundational for other skills. This in turn allowed us to show that this neural system was both malleable with a family-based intervention and that this malleability was specific to the intervention model that involved more emphasis on caregiving broadly, and on key pathways associated with language and stress specifically. While only one example, and one which needs replication and further study in other cultural and implementation contexts as discussed below, this nonetheless demonstrates the potential utility for evidence from cognitive neuroscience to inform approaches to the amelioration of socioeconomic disparities in multiple ways.

Expanding the intervention model

Cultural adaptation

The initial evaluation described above was limited to children from monolingual, native English speaking families. This allowed us to conduct a 'proof-of-concept' evaluation on a smaller scale, but it did not result in a program that could be implemented with or had been tested with the broader population of children served by Head Start. In our region, for example, a number of preschool students came from Spanish-speaking families and had been excluded from participation in the initial study. Thus, we sought to expand the program for work with Spanish-speaking Latino families, and in order to accomplish this it was necessary to conduct a rigorous cultural adaptation of the program. This work was critical, as in order to implement successful programs in broader contexts, it is necessary to systematically consider how cultural differences may affect program acceptability. Indeed, most evidence-based programs for families are developed and assessed with nonminority participants (Dumas, Arriaga, Begle, & Longoria, 2010), and research on the effectiveness of family-based interventions with underserved and diverse populations is relatively scarce (Mejia, Leijten, Lachman, & Parra-Cardona, 2016).

Our first adaptation was implemented with Latino families in Oregon who speak primarily Spanish. To do this, we employed the well-known Cultural Adaptation Process (CAP) model (Domenech Rodriguez & Wieling, 2004), which involves working closely with the target community (e.g., Barrera Jr, Castro, Strycker, & Toobert, 2013). Prior work indicates that CAP has been used successfully to modify a parent training program both within the US (e.g., Domenech Rodríguez, Baumann, & Schwartz, 2011) and internationally (Baumann, Domenech Rodríguez, Amador, Forgatch, & Parra-Cardona, 2014). The three-phase CAP model emphasizes working closely with community stakeholders in a systematic, iterative process.

Details of our work on this adaptation can be found elsewhere (Pakulak et al., 2017); here we highlight select examples of the adaptation. The CAP model involved soliciting input from multiple focus groups, and this input informed several general changes. This began with the name of the intervention, which was changed to *Creando Conexiones: Familias Fuertes, Cerebros Fuertes* [Creating Connections: Strong Families, Strong Brains]. Another general change was the addition of a half hour of socialization time to each parent group meeting in response to feedback that Latino families would benefit more from the small-group format with additional time to eat and socialize with other parents and the interventionists. In response to feedback that groups of Latino parents might include more variability in levels of education and/or literacy, we minimized the number of words in curriculum materials for parents when possible.

Most changes to curriculum materials involved adjustments in framing to make strategies more culturally appropriate or relevant. Many PCMC-A strategies aim to help parents change how they use language with their children in ways both increase the amount of attention children pay to parent language and also foster good language development. As an initial step examples are provided that seek to make parents more aware of patterns of their language use with their children. For example, with a strategy focused on "meaningless questions," in which the child's answer does not matter, we asked parents to imagine how they would feel if they declined a friend's offer of coffee and then the friend insisted on serving them coffee. However, input from focus groups suggested that Latino parents would not identify with this example, as it would be considered culturally rude not to accept food or drink at a friend's house. To address these concerns, we modified the example to be more culturally relevant by reframing it to take place in a restaurant where a waiter insisted on serving coffee, while still accomplishing the goal of communicating the effect of being asked a meaningless question (Figure 2).

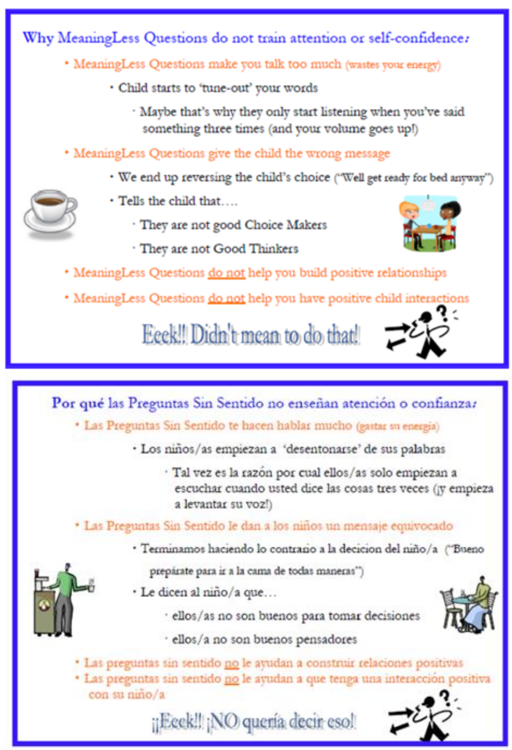

Figure 2 - Example of adapted materials from parent training component. Upper panel shows version used with monolingual native English speakers. Lower panel shows version used in adapted version used with Spanish-speaking families. See text for details of adaptation.

Our second adaptation also involved working with Spanish-speaking families, but in a different cultural context. As part of a line of translational research in Colombia (e.g., Attanasio et al., 2014), the opportunity arose to conduct a pilot study in Medellín, Antioquia, Colombia. While the local adaptation of materials for Spanish-speaking families in Oregon provided an important foundation, several additional challenges were presented by differences in both culture and environment (i.e., Medellín is more urban than our community in Oregon). Because it is especially important to rigorously assess the fit of an intervention to the target population when adapting an intervention to a different country (Baumann et al., 2014), we again used the CAP model for this adaptation.

Again, further details of the adaptation for the Colombia context can be found elsewhere (Pakulak et al., 2017). Here we highlight the primary adaptation that resulted from that study, which is illustrative of the importance of a careful consideration of cultural differences and working closely with stakeholders in the target population. In both the original PCMC-A intervention and the Oregon adaptation, Creando Conexiones, we used an overarching car metaphor to convey respect for parenting practices inherited from parents and other family members, with intergenerational parenting practices described as being akin to a car that might be inherited. This is compared throughout the parent curriculum to inherited parenting practices: just as one might be pleased overall with an inherited car, one still might seek to make small improvements. Similarly, a parent might be pleased overall with inherited parenting practices but still seek improvements by adding "new tools to the parenting toolbox." Because most lower SES families in Medellin do not own cars, focus groups in Colombia identified this overarching metaphor as problematic. Through brainstorming, an alternate and more culturally appropriate metaphor was identified: a family recipe. This metaphor (i.e., one might like a family recipe but still seek to make minor improvements) was well received in the subsequent pilot study and thus retained and provides an example of an adaptation of the intervention delivery style to be more culturally appropriate without changing the underlying components of the intervention (Figure 3).

Creando Conexiones: Metáfora de la receta para la cultura del hogar
Considere la Posibilidad de "Herramientas Generacionales"

- Herramientas heredadas de sus madres/padres…abuelas/abuelos
- ¿Qué "Receta" heredo?
  - Frijoles ¿con coles o sin coles?
  - ¿Chicharron o chorizo?
  - ¿Patacón o tajada de maduro?
  - ¿Horas de elaboración o minutos?
  - ¿En fogon de leña o en estufa?
  - ¿Sabroso?
  - ¿Orgulloso de preparalo en casa?
  - ¿Disfruta cocinando ese plato?
- ¿Con qué "Receta" quiere usted alimentar a su familia?
  - ¿Cómo la transmitirá en las diferentes generaciones?
  - ¿Necesita cambiar unos ingredientes o cambiar la receta por completo? ¡Usted decide!

¿Qué hay en su recetario familiar?

Piense acerca de su "Recetario Familiar", identifique los ingredientes o métodos para cocinar que ya no se usen por dificultades de espacio o tiempo.

Pruebe nuevas recetas, decida si las nuevas recetas "funcionan" para su familia.

Tenga a la mano los ingredientes para sus nuevas recetas.

Figure 3 - Example of adapted materials from parent training component from the adaptation in Medellin, Colombia. Upper panel shows version used with Spanish-speaking families in the United States. Lower panel shows version used in adapted version used with Colombian families. See text for details of adaptation.

The next step in this work was a small-scale pilot study in which Colombian preschool staff were trained in the program and delivered the adapted curriculum to 12 local families. The goal of this pilot study was to assess whether the curriculum could be implemented by local Colombian staff with fidelity to core components and whether Colombian families would participate and report satisfaction with the program. Fidelity assessments confirmed that local staff delivered the program with high implementation fidelity, which was important in order to demonstrate that it could be delivered by interventionists socialized in Colombian culture. In addition, families in the pilot study were enthusiastic about the program, with 10 of 12 families attending 88% of parent group meetings. Results from a questionnaire assessment revealed high satisfaction and use of strategies, and also provided feedback about the cultural suitability of the materials. With this groundwork in place, future work can examine whether the adapted intervention leads to similar gains in outcomes for children and their parents in the Colombia context.

Scalable model of intervention

The above work demonstrated that the original PCMC-A intervention could be culturally adapted for Spanish speaking families in two cultural contexts. However, a second question concerning generalizability of the PCMC-A intervention was whether it could be scaled up for delivery within Head Start. That is, in the original PCMC-A work described above, the intervention was delivered exclusively by lab staff in evenings outside of the regular Head Start schedule and to only a subset of students served by Head Start. Given the documented efficacy of PCMC-A in this context (Neville et al., 2013), we next sought to develop a scalable delivery model of the intervention – one that could be integrated into existing Head Start services and implemented by Head Start staff to all students in the Head Start population.

This 'scale-up' had the potential to produce an intervention model that could be delivered by Head Start staff and would therefore be more amenable to wider implementation by other Head Start and preschool services. In order to pursue this goal, we formalized and expanded our collaborative partnership with our local Head Start partners. A more detailed account of this process can be found elsewhere (O'Neil, Pakulak, et al., 2019), and here we highlight features of this delivery model informed by the evidence on disparities discussed above and by results from our smaller-scale study (Neville et al., 2013).

In order to clearly distinguish the new scaled-up delivery model from PCMC-A, we renamed it by adopting a back-translation of Creando Conexiones, the name used in the cultural adaptation into Spanish (Pakulak et al., 2017). The full back-translated name, Creating Connections: Strong Families, Strong Brains (henceforth CC), captured program goals of improving relationships between parents and their children and of increasing the degree of integration between the classroom and home environment, while also alluding to mechanisms of experience-dependent plasticity (e.g., synaptogenesis).

Because the child component of the original PCMC-A intervention was delivered in small groups in a classroom setting, in the scaled-up model we integrated these activities directly into the classroom. Given the results discussed above, we wanted to maintain and expand the emphasis on family stress in CC and also recognized an opportunity to expand this emphasis. To this end, we integrated selected parenting strategies into the classroom adapted for use by teachers. These were framed as classroom management strategies to foster positive child development, in a structured sequence to scaffold the developmental skills being targeted. One potential advantage of incorporating these strategies into the classroom was to increase consistency across the home and school contexts. That is, to the extent that parents implemented some of the same strategies that teachers were using in the classrooms, we reasoned that children would experience reduced stress across environments. As well, since teachers were the first to introduce these strategies within the classroom, we expected that children would be more responsive when parents began implementing the strategies as their children would already be familiar with the strategies from the classroom environment. We expected this would increase parents' success with – and thus use of – the suggested strategies.

The parent component of CC maintained the weekly parent group meeting format employed in PCMC-A. The primary modification to this component addressed sustainability in the Head Start context, as the small-group format of PCMC-A (i.e., caregivers of 4-6 children) was not considered amenable to broader implementation. To address this, we modified the format of parent group meetings to accommodate up to 30 caregivers with a combination of large-group curriculum instruction and small-group discussion and role playing. To accommodate this change, and to improve the sustainability of the model, CC parent component meetings involved multiple Head Start co-facilitators who ran the small-group discussions following large-group instruction by one of our interventionists. This model also allowed selected HSOLC co-facilitators to transition into the lead interventionist role, thereby improving long-term sustainability. The parent component of CC was delivered during the winter of the school year to facilitate acquisition of outcome measures. Laboratory measures were acquired during a three-month period in the fall before the parent component, and again during another three-month period in the spring.

We also expanded our assessment battery with outcome measures informed by the evidence from cognitive neuroscience studies of poverty discussed above and our previous findings. Given the central role of chronic stress in relationships between early adversity and brain systems important for attention and self-regulation, as well as the reductions in self-reported parenting stress we documented, we sought to more directly assess the hypothesized effects of CC on these systems in both children and parents. An emerging literature reveals associations with early adversity and an important aspect of stress regulation, the function of the autonomic nervous system (for reviews, see Pakulak et al., 2018; Propper & Holochwost, 2013). Electrophysiological measures of heart rate variability have been found to be a robust biomarker of individual differences in this system (e.g., Hemingway et al., 2005) that can be acquired simultaneously with our measures of brain function. To measure brain function for selective attention in children and parents, we are employing the paradigm we have used successfully with both child and adult participants (e.g., Giuliano et al., 2014; Neville et al., 2013), and in adults we are also measuring brain function for inhibitory control employing a stop-signal task (Berkman, Kahn, & Merchant, 2014). Along with these measures of brain function in both children and parents, we are simultaneously acquiring electrophysiological assessments of both branches of autonomic nervous system function.

In addition to more precise and theoretically-informed measures of intervention outcomes, these refined assessments are already providing further evidence on the relationship between early adversity and regulatory neurobiological systems. A study employing pre-test data from these assessments in children has replicated and expanded on our previous findings regarding early adversity and selective attention (Giuliano et al., in press). Consistent with our previous results (Stevens et al., 2009), increased exposure to socioeconomic risk factors was associated with differences in distractor suppression in preschool-aged children. In addition, this relationship was mediated by sympathetic nervous system (SNS) function, suggesting that relationships between SES and selective attention may be accounted for by chronic activation of the SNS. These results underscore the importance of simultaneously measuring both sympathetic and parasympathetic contributions to regulatory behavior, and also offer new explanatory mechanisms with implications for the refinement of theories on the biological embedding of early experience and outcomes across the lifespan.

The study described above is part of a systematic line of research in our lab investigating the relationship between early adversity and contributions of autonomic physiology to the development of neural mechanisms of cognition in children. Thus, in addition to the potential of cognitive neuroscience to inform efforts to combat poverty in ways described above, another manner in which cognitive neuroscience is a valuable tool is in the ability to combine methodologies for studying brain function with methodologies for studying other aspects of neurobiological function that are sensitive to early adversity. Such multi-methodological approaches can provide more specificity that will improve our mechanistic understanding of these relationships, which in turn can inform evidence-based refinements of interventions seeking to address poverty.

Conclusions

We opened this chapter by asking what value cognitive neuroscience has for the study of relationships between socioeconomic background and later life outcomes. We argued that the careful use of neuroscience data can provide valuable insight into the mechanisms whereby inequality becomes biologically embedded and associated with a wide and disparate range of life outcomes (e.g., McEwen & Gianaros, 2010; Nusslock & Miller, 2016; Pakulak et al., 2018; Ursache & Noble, 2016), with the potential to guide the development and evaluation of programs designed to improve outcomes for those in poverty. The interdisciplinary line of research described in this chapter provides one example of such efforts, where theories and findings emerging from neuroscience research were applied to the design of a two-generation intervention for families in poverty. Our focus on attention and language outcome measures was guided in part by evidence from cognitive neuroscience, as was our focus on family-based strategies targeting pathways linking socioeconomic background to different outcomes. In particular, elegant neuroscience research on the role of chronic stress in development guided both initial curriculum decisions as well as subsequent studies focused on broader implementation and improved assessment. Importantly, these studies involved collaboration across cultures as well as across disciplines, with specialists in education, cultural adaptation, stress physiology, and economics among others. As we prepare to close the chapter, we turn to a set of questions concerning the research foci that should be prioritized in coming decades, as well as the value of interdisciplinary interactions and discussions.

In coming decades, we believe – perhaps ironically – that it will be *communication, sharing, and collaboration* between disciplines, more than specific new research findings or directions, that should be prioritized. While different disciplines generally use different methodologies and tools to investigate research questions, there is often striking convergence in conclusions across levels and approaches. One example of this is the set of findings regarding the role of stress physiology and early experience. The elegance of animal models of stress and deprivation is invaluable for demonstrating the causal role of early caregiving behavior on child outcomes, as well as identifying specific neurobiological pathways that mediate these changes. These findings can in turn inform how we conceptualize and address some disparities in studies of humans. Neuroscience models that elucidate the biological embedding of social status also provide empirical data that can shift away from narratives that characterize poverty as individual failure and move toward those that recognize the complex interactions between social structures and biological characteristics that shape outcomes early in development and across the life span (e.g., McEwen & McEwen, 2017).

More concretely, part of increasing communication among disciplines will be a greater reliance on interdisciplinary teams of researchers. When we talk only to those researchers who have a similar theoretical lens and analytic approach, our work may be well received, but it is also likely to have only a more limited impact. To the extent that studies involve collaboration across disciplines (e.g., neuroscience, cognitive neuroscience, social and developmental psychology, genetics, epidemiology, prevention and intervention science education, sociology, economics, and public policy), and integrate multiple methodologies (e.g., stress, physiology, health), there is more potential for important crosstalk. There are several recent examples of how such collaborations can push the boundaries of interdisciplinary communication and collaboration as a means of identifying convergence across disciplines (e.g., McEwen & McEwen, 2017; Perry et al., 2018).

It is also clear, especially in the study of poverty, that collaborations should involve not only researchers from different disciplines but also colleagues from different cultural contexts (e.g., Attanasio et al., 2014; Neville, Pakulak, & Stevens, 2015; Pakulak et al., 2017). The importance of this work is underscored by evidence that there is more cross-cultural variability in behavioral performance than previously believed (Henrich, Heine, & Norenzayan, 2010); thus it would be naïve to impose findings and programs from one cultural context to another without a careful consideration of cultural differences. Such consideration can also inform the broader study of poverty by elucidating putative different cultural pathways by which poverty can affect neurobiological systems, as well as potentially culturally-specific resilience factors that could be adapted for other cultures.

To these ends, interdisciplinary discussions and collaborations are critical to progress in the field. The real game changers in science – and science for the public good – will be the recommendations that emerge from converging evidence. Something that was clear during the Erice discussions was the importance of explicitly acknowledging different levels of analysis and approaches, and learning about and embracing the work of other disciplines. This is not done as lip service, but instead represents an important way of acknowledging the convergence across fields and the complexity of a problem. By doing so, we hope to promote a broader understanding of the phenomenon under study, even when our particular emphasis might be on one level of analysis or one specific component of an issue. At the same time, as researchers we will of course have different foci and approaches. Trying to do everything at once is impossible, and without a necessary degree of focus an issue becomes completely intractable. There is something in the humility of knowing that a particular project or research study is just a small piece of puzzle, and that beyond doing 'our study' we must also be willing to engage the work of others. This interdisciplinary engagement can help us bring more nuance to our own work, and to our understanding of whether or how our work might relate to a broader context.

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7

RELATIONSHIPS BETWEEN SOCIOECONOMIC STATUS AND READING DEVELOPMENT: COGNITIVE OUTCOMES AND NEURAL MECHANISMS

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Introduction

Learning to read is one of the most important achievements of early childhood, and sets the stage for future success. Even prior to school entry, children's foundational literacy skills predict their later academic trajectories (Duncan et al., 2007; La Paro & Pianta, 2000; Lloyd, 1969; Lloyd, 1978). Children learn to read with differing levels of ease, with an estimated 5-17% of school-age children who struggle with reading acquisition (Shaywitz, 1998). The individual variation in children's reading skills can be predicted by genetic, environmental, academic, and sociodemographic factors (for review, see Peterson & Pennington, 2015). This chapter focuses on the relationship between reading development and socioeconomic status (SES), with attention to both cognitive outcomes and neural mechanisms. First, we describe SES and its relation to academic achievement in general, and reading development in particular. Second, we examine environmental factors that can potentially give rise to socioeconomic disparities in reading, such as early language/ literacy exposure and access to books. Next, we explore the link between SES and reading disability (RD), including a focus on intervention approaches and treatment response. Finally, we summarize remaining questions and propose future research priorities.

Socioeconomic status: Definition and measurement

An individual's SES refers to their social and economic resources, and the consequent social status that arises from these resources (Bradley & Corwyn, 2002). SES is a complex, multi-faceted, and intangible construct, with multiple measurement tools that aim to capture distinct aspects. Objective measurement of SES typically combines a three-pronged assessment of an individual's educational attainment, income, and occupation (Bradley & Corwyn, 2002; Duncan & Magnuson, 2012; Ensminger & Fothergill, 2003; Green, 1970; U.S. Bureau of the Census, 1963; White, 1982). Perhaps the best known measure is the Hollingshead Index, which combines a weighted sum of all householders' education and occupation ratings (Hollingshead, 1975). Other measures include neighborhood SES (Minh, Muhajarine, Janus, Brownell, & Guhn, 2017), income-to-needs ratios (Duncan, Brooks-Gunn, & Klebanov, 1994), and principal component analysis of multiple factors (e.g., Noble, Farah, & McCandliss, 2006a; Noble, Wolmetz, Ochs, Farah, & McCandliss, 2006b). In contrast to objective measures of SES, subjective assessments of social status measure *perceived* financial and social standing with respect to local and national communities (Adler, Epel, Castellazzo, & Ickovics, 2000; Cundiff, Smith, Uchino, & Berg, 2013). Pediatric research relies on caregivers in the home (e.g., parents) to offer information on SES through one or more of these approaches to measuring SES.

In practice, one or a few measures typically serve as a proxy for socioeconomic index, though SES is not a unitary construct with a simple unidirectional influence on child outcomes. SES correlates with many intertwined developmental influences including stress, nutrition, toxin and violence exposure, access to and quality of healthcare, and educational resources. Associations between SES and child development are best understood within a wider social, physical, and environmental context.

The "achievement gap"

The "achievement gap" refers to the disparity in academic performance and/or educational attainment between students from disparate backgrounds, typically by either racial background or socioeconomic determinants (Reardon, 2011). The achievement gap has been of great interest to researchers since the 1960s, when a sweeping review of American education, as a part of the "War on Poverty"[8], revealed that the strongest determinant of a child's educational success was his/her family background (Coleman et al., 1966). Specifically, white and higher-income students

[8] Political program of the American president Lyndon Johnson (1963-1969), which included the provision of special preschool education for children from poor households, as well as vocational training for young people who had dropped out of school and jobs in community services for young people who lived in poor neighborhoods (Editor's note).

performed several grade levels higher in both reading and math than black and lower-income students (Coleman et al., 1966).

Evidence for the achievement gap has accumulated since the early recognition in educational disparities. While the racial achievement gap has shrunk significantly over the last half century, the income achievement gap has more than doubled. This increase in the achievement gap translates to scores 1.25 standard deviations higher on standardized tests, on average, for wealthier students compared to their lower SES peers (Reardon, 2011; U.S. Department of Education). Similar gaps favoring higher SES students are found in other academic measures including grade point averages (Sirin, 2005; White, 1982), high school completion rates (Brooks-Gunn & Duncan, 1997; Duncan & Magnuson, 2011), and college entry and completion (Bailey & Dynarski, 2011).

Despite its wide-reaching consequences across educational outcomes, the impact of SES is not uniform across all domains. While SES is significantly correlated with memory, cognitive control, and executive functioning, the greatest effects appear in language and reading skills (Farah et al., 2006; Noble, McCandliss, & Farah, 2007; Noble, Norman, & Farah, 2005). Specifically, SES explains nearly a third (32%) of the variance in the language skills of first graders (Noble et al., 2007), nearly twice that of all other cognitive domains studied. Meta-analyses over several decades of studies reveal that SES also explains 30-35% of the variance in broadly defined academic reading measures, which makes it one of the strongest predictors of academic performance (Sirin, 2005; White, 1982).

Socioeconomic disparities are also apparent in individual sub-domains of reading and pre-reading skills. Higher SES background is associated with more positive outcomes in important skills including phonological awareness (Bowey, 1995; Lonigan, Burgess, Anthony, & Barker, 1998; McDowell, Lonigan,

& Goldstein, 2007; Raz & Bryant, 1990), early print knowledge (Hecht, Burgess, Torgesen, Wagner, & Rashotte, 2000; Smith & Dixon, 1995), decoding and early word reading (Hecht et al., 2000; Molfese, Modglin, & Molfese, 2003; Share, Jorm, Maclean, Matthews, & Waterman, 1983; White, 1982), fluency and automaticity (Haughbrook, Hart, Schatschneider, & Taylor, 2017; Stevenson, Reed, & Tighe, 2016), and reading comprehension (Hart, Soden, Johnson, Schatschneider, & Taylor, 2013; Hecht et al., 2000; MacDonald Wer, 2014). Lower SES is also associated with a slower trajectory of literacy growth throughout elementary school (Hecht et al., 2000). Likewise, as children transition in later elementary school from "learning to read" to "reading to learn", disparities in reading often snowball into disparities in other academic domains, which rely on analysis and comprehension of complex texts (Chall, 1983; Chall, Jacobs, & Baldwin, 1990).

Achievement gaps in language and literacy appear to begin very early in childhood, before children enter school (Ginsborg, 2006; Lee & Burkam, 2002; Ramey & Ramey, 2004). Consequently, higher-SES children begin Kindergarten better prepared and with a stronger foundation on which to build literacy skills. Indeed, achievement gaps continue to widen throughout the elementary grades, creating a Matthew effect ("the rich get richer while the poor get poorer") in which good readers improve more rapidly, while struggling readers fall further behind their peers (Chall et al., 1990; Stanovich, 1986).

One phenomenon contributing to these widening gaps occurs outside of the traditional school year. The "summer slump" or "summer slide" refers to the trend in which lower-SES children are vulnerable to academic regression during the summer months between school years; meanwhile, higher-SES students tend to maintain or even gain academic skills (Alexander, Entwisle, & Olson, 2007; Cooper, Nye, Charlton, Lindsay, & Greathouse, 1996; McCoach, O'Connell, Reis, & Levitt, 2006). By the ninth grade, more than half of the income-achievement gap can be explained by differential summer learning during the elementary school years (Alexander et al., 2007), with significant summer learning disparities in reading (Cooper et al., 1996).

Neuroimaging and SES

Neuroimaging research has revealed the neural correlates of SES and academic achievement gaps as well. A study on adolescents aged 13-15 year old from diverse backgrounds showed that the thickness of cortical gray matter in temporal and occipital lobes was associated with both SES and performance on standardized tests, and that cortical differences in these regions accounted for almost half of the income achievement gap (Mackey et al., 2015). Another study of children aged 4-22 years found that differences in the cortical volume of frontal and temporal gray matter explained as much as 20% of test score gaps (Hair, Hanson, Wolfe, & Pollak, 2015). Other studies have confirmed similar relationships between SES, neuroanatomy, and a variety of cognitive domains and/or academic achievement (for reviews, see Brito & Noble, 2014; Farah, 2017; Johnson, Riis, & Noble, 2016).

Several studies have investigated the neural *mechanisms* underlying SES disparities in reading skills. A common neuroimaging tool is functional magnetic resonance imaging (fMRI), which tracks blood flow to brain regions most active during a cognitive task such as rhyming judgments or reading words and/or pseudowords. These studies have found significant relationships between SES and brain activation related to phonological awareness in left perisylvian regions in pre-reading 5 year-olds (Raizada, Richards, Meltzoff, & Kuhl, 2008) as well as in 8-13 year-olds (Demir, Prado, & Booth, 2015; Demir-Lira, Prado, & Booth, 2016). Another study of 6-9 year-olds revealed that SES modulated the relationship between phonological awareness skills and brain activity in left fusiform and perisylvian regions during reading (Noble, et al., 2006b). In particular, lower-SES children exhibited a stronger brain-behavior relationship than their higher-SES peers, who exhibited higher fusiform activation and higher reading scores regardless of their phonological awareness scores (Noble, et al., 2006a; Noble, et al., 2006b). This suggests that low SES multiplies the effect of low phonological awareness to result in weaker decoding skills, while some aspect of higher-SES children's early environments may have buffered the effects of low phonological skill, resulting in increased fusiform recruitment and better reading outcomes.

These cognitive and neuroimaging studies show that the socioeconomic achievement gap is particularly pervasive in language and literacy skills, and these disparities arise long before children arrive at school. These findings raise questions of *how* SES differences in children's language skills arise in the first several years of life and which aspects of higher and lower SES environments influence linguistic and neural development. Answers to these questions require a deeper examination of children's early language environments.

Environmental contributions to SES reading gaps

Given that SES is a multifaceted construct, encompassing economic resources and sociocultural backgrounds, many aspects of higher and lower SES environments likely contribute to early learning[9]. Indeed, the bioecological model of development suggests that SES is a *distal* factor that presumably affects children's neurocognitive outcomes via more immediate, *proximal* environmental influences (Bronfenbrenner & Ceci, 1994;

[9] See Demir-Lira's chapter in this volume (Editor's note).

Bronfenbrenner & Morris, 1998). Two proximal influences that have been frequently found to relate to reading outcomes are children's early exposure to oral language and experience with literacy and reading practices.

The home literacy environment (HLE) characterizes children's early exposure to literacy-related resources, interactions, and attitudes (Shapiro, 1979). HLE encompasses the availability of books in the home, the frequency/quality of storybook reading with young children, caregivers' efforts to teach print-related concepts (e.g., the alphabet), and family members' modeling of reading practices and attitudes toward literacy (Payne, Whitehurst, & Angell, 1994; Sénechal & LeFevre, 2002). Children's early HLE is associated with their later development of oral and written skills, including receptive and expressive vocabulary, listening comprehension and grammatical knowledge, phonological awareness, early letter and print knowledge, and comprehensive reading skills later in school (Bracken & Fischel, 2008; Burgess, Hecht & Lonigan, 2002; Bus, van Ijzendoorn & Pellegrini, 1995; Frijters, Barron & Brunello, 2000; Hood, Conlon & Andrews, 2008; Levy, Gong, Hessels, Evans, & Jared, 2006; Martini & Sénéchal, 2012; Payne et al., 1994; Scarborough & Dobrich, 1994; Scarborough, Dobrich & Hager, 1991; Sénéchal & LeFevre, 2002; Sénéchal, LeFevre, Hudson & Lawson, 1996; Sénéchal & LeFevre, 2014 Sénéchal, Pagan, Lever, & Ouellette, 2008; Storch & Whitehurst, 2001). HLE can reflect SES through specific home environment practices and resources. For example, lower SES is associated with reduced access to reading materials in the home and at libraries (Feitelson & Goldstein, 1986; Neuman & Celano, 2001), or less frequent teaching of print concepts or reading to young children (Burgess et al., 2002; Chaney, 1994; Feitelson & Goldstein, 1986; Harris & Smith, 1987; Karrass, VanDeventer, &

Braungart-Rieker, 2003; Leseman & Jong, 1998; McCormick & Mason, 1986; Phillips & Lonigan, 2009).

However, there is also great variability within SES factions, with certain lower SES families reading to children more often than some higher SES families (Chaney, 1994; Farver, Xu, Eppe & Lonigan, 2006; Senechal, 2006; Smith & Dixon, 1995; Storch & Whitehurst, 2001; Van Steensel, 2006). This within-group variability allows for statistical analysis of the factors most strongly linked to reading outcomes, and several studies have found that the HLE predicts children's literacy achievement over and above SES alone (Bracken & Fischel, 2008; Christian, Morrison, & Bryant, 1998; Gottfried, Schlackman, Gottfried & Boutin-Martinez, 2015; Payne et al., 1994; Rodriguez & Tamis-LeMonda, 2011; Smith & Dixon, 1995). Moreover, mediation analyses reveal that individual differences in HLE partially or fully explain relationships between SES and literacy development (Chazan-Cohen et al., 2009; Foster, Lambert, Abbott-Shim, McCarty, & Franze, 2005; Hamilton, Hayiou-Thomas, Hulme, & Snowling, 2016; Kiernan & Huerta, 2008; Krishnakumar & Black, 2002). Yet these need not be static phenomena; intervention studies reveal that programs targeting parents' literacy activities can have a significant effect on children's reading development (for review, see Sénéchal & Young, 2008).

Oral language exposure is another salient aspect of HLE, which shows even earlier socioeconomic disparities. In a landmark study, Hart and Risley (1992, 1995) followed 42 socioeconomically diverse children from 7 months to 3 years of age. They found that children from the lowest-SES families heard fewer than a third of the words per hour heard by higher-SES children early on, which aggregated to a gap of thirty million words by age three (Hart & Risley, 1995). Disparities were not only evident in the *quantity* of linguistic input, but also the *quality*. Higher SES parents also used more diverse vocabulary, more affirmatives and fewer prohibitions, more questions, and more linguistically beneficial responses such as repetitions, expansions, and extensions of child utterances, and they were generally more responsive, affirmative, and encouraging (Hart & Risley, 1995). The combination of these qualitative variables explained over 60% of the variance in children's IQs at 3 years of age.

More recent studies have found socioeconomic differences in a number of other qualitative aspects of language exposure. Higher SES has been associated with more favorable outcomes in aspects of language including the mean length of utterance (Hoff, 2003; Hoff & Naigles, 2002; Hoff-Ginsberg, 1991; Rowe, 2008), syntactic complexity and diversity (Huttenlocher, Vasilyeva, Cymerman, & Levine, 2002; Naigles & Hoff-Ginsberg, 1998), contingency and contiguity (Conway et al., 2018; Goldstein, King, & West, 2003; Hirsh-Pasek et al., 2015; Hoff-Ginsberg, 1991; Hoff-Ginsberg, 1998; Reed, Hirsh-Pasek, & Golinkoff 2016; Smith et al., 2018; Tamis-LeMonda, Kuchirko, & Song, 2014), and decontextualized references (Rowe, 2012). In addition, SES disparities have been shown regarding conversational exchanges (Hirsh-Pasek et al., 2015; Romeo, Leonard et al., 2018; Zimmerman et al., 2009) and nonverbal gestures and referents (Cartmill et al., 2013; Iverson, Capirci, Longobardi, & Cristina Caselli, 1999; Pan, Rowe, Singer, & Snow, 2005; Rowe & Goldin-Meadow, 2009; Rowe, Özçalişkan, & Goldin-Meadow, 2008).

However, as with HLE, there is also considerable variation in language exposure within socioeconomic factions (Gilkerson et al., 2017; Hirsh-Pasek et al., 2015; Rowe, Pan, & Ayoub, 2005; Weisleder & Fernald, 2013). Quantity and/or quality of children's language exposure predict unique variance in children's language skills above and beyond SES (Romeo, Leonard, et al., 2018; Rowe, 2012; Weisleder & Fernald, 2013), and even mediate the SES achievement gaps in language skills (Hoff, 2003; Huttenlocher et al., 2002; Romeo, Leonard, et al., 2018; Romeo, Segaran, et al., 2018; Rowe & Goldin-Meadow, 2009). Upon school entry, these differences in early oral language skills often persist and transform into disparities in literacy acquisition, explaining a large proportion of the achievement gaps in reading, spelling, and other cognitive and academic skills in elementary school (Durham, Farkas, Hammer, Bruce Tomblin, & Catts, 2007; Marchman & Fernald, 2008; Morgan, Farkas, Hillemeier, Hammer, & Maczuga, 2015; Walker, Greenwood, Hart, & Carta, 1994).

While many studies have investigated neural correlates of SES, comparatively few have investigated mechanistic relationships between proximal environmental influences such as HLE and oral language exposure, and neural development. For example, a research study with 3-5 year-olds asked parents about their children's access to books, frequency of shared reading, and variety of books read, and found that greater reading exposure was associated with greater activation during a story-listening fMRI task in the left parietal-temporal-occipital association cortex, a region involved in mental imagery and narrative comprehension (Hutton et al., 2015). A similar study measured the real-world language exposure of 4-6 year-old children over the course of two days, including the number of words spoken by adults and the number of dialogic conversational turns between adults and the enrolled children. While the sheer number of adult words was not associated with neural measures, the number of conversational turns correlated positively with activation in known language areas in left lateral prefrontal region during story listening (Romeo, Leonard, et al., 2018), as well as with the structural connectivity between this region and left posterior temporal regions known to subserve language processing (Romeo, Segaran et al., 2018). Furthermore, both structural and functional measures mediated

SES disparities in children's language skills, indicating both environmental and neural mechanisms underlying the linguistic achievement gaps preceding literacy.

Relationship between SES and reading disability

Reading disability (RD) is a language-based learning disability characterized by persistent difficulty in reading acquisition and development (Peterson & Pennington, 2015; Shaywitz, Morris, & Shaywitz, 2008). RD is the most prevalent specific learning disability (Lerner, 1989); about 80% of children with learning disabilities struggle in reading (Lyon, Shaywitz, & Shaywitz, 2003). Despite average cognitive skills, children with RD may exhibit deficits in word recognition, decoding, text-level fluency, reading comprehension, or multiple sub-domains of reading (Lyon, Shaywitz, & Shaywitz, 2003). Etiologically, RD runs in families, and exhibits a high degree of heritability (Harlaar, Spinath, Dale, & Plomin, 2005).

The prevalence of reading challenges differs across the SES continuum however. For example, low-income fourth and eighth graders have scored at "below basic" reading levels at more than twice the rate of their higher-income peers (U.S. Department of Education). Additionally, lower-income students are diagnosed with specific learning disabilities at significantly higher rates (Shifrer, Muller, & Callahan, 2011), and exhibit a disproportionately higher risk of being diagnosed with developmental dyslexia (Peterson & Pennington, 2015), although reduced access to diagnostic care may prevent many lower-SES parents from seeking diagnoses of reading disability for their children.

Indeed, several studies have revealed gene by environment interactions in the heredity of RD, whereby SES modulates the risk for developing reading difficulties in children with familial risk (for review, see Becker et al., 2017). In most cases, the genetic contribution is greatest and environmental contribution lowest at the higher end of the SES spectrum, while the reverse is true at the lower end, with a greater influence of environmental factors in lower SES circumstances (Friend, DeFries, & Olson, 2008; Mascheretti et al., 2013). This suggests that, in low SES environments, reduced HLE and oral language exposure may intensify a genetic predisposition for RD and/or may prevent children with low genetic risk from achieving their full reading potential. Indeed, low HLE better predicts diminished reading skills over and above a familial risk of dyslexia (Dilnot, Hamilton, Maughan, & Snowling, 2017). Neuroanatomically, in children with RD, SES is more strongly correlated with the cortical structure of reading related brain regions than clinical reading scores (Romeo et al., 2017). This etiological and neurological heterogeneity in RD suggest that the effectiveness of treatment programs may vary based on differences in children's environmental backgrounds.

Given the wealth of literature focused on the predictors of success in various reading interventions, surprisingly few studies have investigated socioeconomic differences in treatment response. According to recent reviews of studies aiming to predict children's response to literacy interventions (Barquero, Davis, & Cutting, 2014; Lam & McMaster, 2014), fewer than 30 percent of behavioral studies and only two neuroimaging studies have examined SES as a predictive factor. These reveal mixed results - two smaller studies find that *higher* SES predicts better treatment response (Hatcher et al., 2006; Morris et al., 2012), while one finds that *lower* SES predicts better treatment response and commensurate neuroanatomical changes (Romeo et al., 2017). These opposite results may arise as result of fundamental differences in the treatment programs themselves (e.g., content domain of focus, format, treatment timing). For example, higher-

SES children with RD may benefit more from school-based programs with distributed phonologically-focused sessions over a longer duration, whereas lower-SES children with RD may respond best to intensive, short-term interventions with an orthographic focus during non-academic summers. Whatever the reason, these results suggest that the efficacy of certain treatment approaches may depend on the etiology of the reading struggle amongst various other environmental factors.

The future of SES and reading research

The last half century has seen a dramatic increase in research on academic achievement gaps between students from higher- and lower-income backgrounds, finding a disproportionate effect of SES on the development of children's reading skills. Since then, numerous studies have identified early language and literacy exposure as proximal influences driving these disparities, both independently and in confluence with genetics. The identification of neural mechanisms by which the environmental factors may contribute to academic and cognitive development has also advanced understanding of SES and reading. The juncture of education and neuroscience fields invites exciting opportunities for both basic and translational research.

Perhaps the most pressing issue is the continuing investigation into the heterogeneity of etiologies of reading difficulties. While there are both genetic and environmental contributions to variation in children's language and reading skills, it is clear that environmental factors have a particularly strong influence early in life, during sensitive periods when the brain is most plastic (Hayiou-Thomas, Dale, & Plomin, 2012; Logan et al., 2013; Tierney & Nelson, 2009). As was previously mentioned, SES disparities in early language and literacy environments suggest that the etiology of reading disabilities may vary by socioeconomic background, such that RD in lower-SES children may be triggered by limitations in resources in the environment, while RD in higher-SES children may have a greater genetic basis (Haughbrook et al., 2017). Such etiological differences may give rise to different cognitive and neural phenotypes of the disorder, which in turn may respond differently to specific treatments. Educational neuroscience is just beginning to utilize such "precision medicine" techniques, using behavioral, demographic, and neural markers to predict individualized treatment outcomes and employ the most effective programs for each child (Gabrieli, Ghosh, & Whitfield-Gabrieli, 2015). In this regard, future research should consider investigating biomarkers that can inform educational practice and RD treatment on an individualized level.

Relatedly, future RD studies of both baseline neurocognitive descriptors and treatment response should investigate SES as a variable of interest and enroll participants across a wide range of diverse demographic variables. The vast majority of research on reading development, and most of cognitive development at large, has relied on "convenience samples," of participants that frequently skew toward higher-income and more highly educated individuals who both have an awareness/appreciation of research and the time to participate. These samples are often referred to as "WEIRD"[10] (Western, Educated, Industrialized, Rich, and Democratic) (Henrich, Heine, & Norenzayan, 2010), and these psychology and neuroscience findings achieved with restricted populations may not generalize more broadly (LeWinn, Sheridan, Keyes, Hamilton, & McLaughlin, 2017; Nielsen, Haun, Kartner, & Legare, 2017). Although adopting more representative sampling approaches will likely not overhaul all of the fundamental findings

[10] WEIRD is an acronym that refers to people with a western profile, high educational level, from industrialized countries, rich and with democratic systems - that is, as long as the research studies only include participants with such profiles, the results should consider biased (Editor's note).

in reading research, it certainly has the potential to alter our understanding of reading development and the treatment of reading disabilities.

Finally, as research on the neuroscience of poverty continues to expand, researchers must take great care in streamlining measurement of SES and related factors. Parental education and family income are not interchangeable measures; nor are they universally meaningful across cultures, or the best index of the psychosocial stressors and/or buffers present in adverse situations. Future research expand beyond these broad, distal measures of sociocultural context, by delving deeper into proximal factors that presumably act directly on cognitive development, such as home literacy and language exposure. With improved understanding on which precise environmental variables contribute meaningfully to language and literacy development, as well as the underlying neural mechanisms, the field can build more effective interventions for at-risk children.

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8

POVERTY AND NEURODEVELOPMENT IN EARLY CHILDHOOD: STRATEGIES TO PROMOTE EQUITY OF OPPORTUNITIES IN COGNITIVE AND EMOTIONAL DEVELOPMENT

Alejandra Carboni, Hernán Delgado, Verónica Nin

Introduction

Several studies show that the environment influences development, and that neurocognitive development in particular is strongly associated with the socioeconomic context (Brito & Noble, 2014; Pavlakis et al., 2015). However, since the way concepts such as socioeconomic level (SES), social inequality, or poverty are defined can determine the way in which their associations with development are studied, as well as the strategies that are implemented to mitigate its effects, this phenomenon is complex and under continual review due to its epistemological implications (Hermida et al., 2010). SES is a measure that attempts to capture average status and social position, usually characterized by the combination of indices such as educational level, type of education, and per-capita family income, among others (Krieger, Williams, & Moss, 1997).

In general, research on childhood poverty and development has shown that neurodevelopment is modulated by different biological and sociocultural factors. However, depending on the timing, the duration of exposure, the co-ocurrence of factors, and an individual's susceptibility, the effects of these factors will be different. Traditionally, approaches that consider clinical and educational paradigms predominate, and the effects most commonly associated with social vulnerability have been lower IQ scores, a higher incidence of learning disorders, delays in development, and decreases in school attendance and total years of schooling completed (Lipina et al., 2004). Mostly, these studies have been based on measures of general intelligence. Although this allows the identification of the relationships with cognitive performance variables such as verbal comprehension, short- and long-term memory, reasoning, and processing speed, among others, these measures are not necessarily representative of the multifactorial nature of intelligent behaviors (Sternberg & Kaufman, 1998). Likewise, these measures have little sensitivity to ethnic and cultural differences (Bronfenbrenner & Ceci, 1994; Sternberg, 1999).

The Executive function (EF) framework addresses some of these obstacles, as the EF framework permits the discrimination of basic cognitive processes that would be less dependent on the cultural context (Fagan III, 2000; Rogoff & Chavajay, 1995). Research based on the EF framework has shown that EFs have a strong association with the socioeconomic context. This research indicates that children belonging to lower SES homes may have, on average, lower performance in tasks that evaluate cognitive processes that are part of EF compared to children from medium or higher SES backgrounds (Farah et al., 2006; Lipina et al., 2005; Noble, Norman, & Farah, 2005).

EFs comprise the set of skills involved in the control and coordination of information in the service of goal-directed actions, as well as aspects related to self-regulation (Miller & Cohen, 2001). Despite the existence of several theoretical models, there is consensus in classifying EFs as *core* or *higher-order* (Diamond & Ling, 2016). According to this model, *core* EF skills are inhibitory control, cognitive flexibility, and working memory, while higher-order EFs (which develop from the core skills) include planning, problem solving, and reasoning. To this model we can add another classification that groups EFs as either *cold* or *hot* (Zelazo, Qu, & Kesek, 2010). Hot EFs include self-regulation skills such as social intelligence and decision making in emotionally or motivationally relevant contexts (Figure 1).

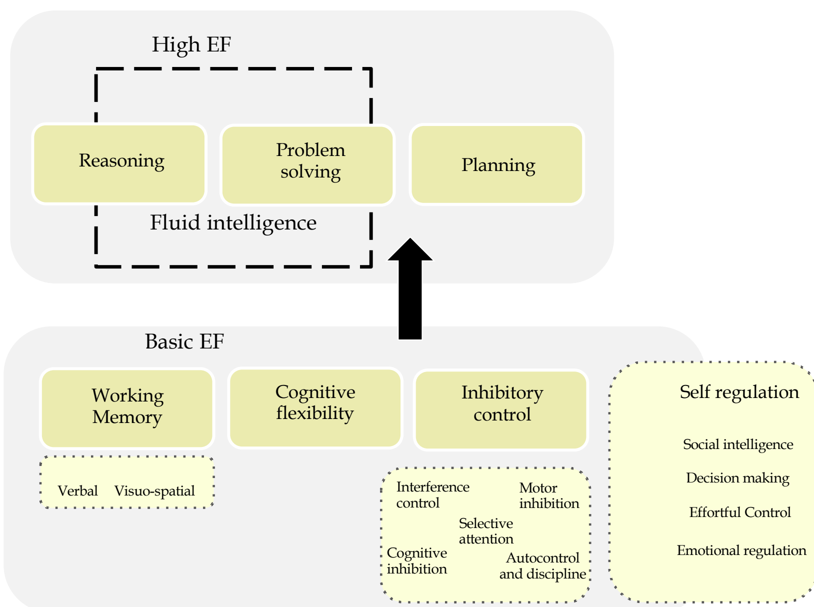

Figure 1 - Diagram of the cognitive domains involved in the definition of EF. Sub-processes and mental abilities closely related to inhibitory control appear in a dotted box. The concept of self-regulation largely

overlaps with that of inhibitory control, but is often used in relation to aspects of emotional regulation and in social contexts, and is associated with the concepts that appear in the box on the right (Addapted from Diamond, 2016).

The development of EF during early childhood lays the basic foundation for the development of higher cognitive functions during the rest of the lifetime (Garon, Bryson, & Smith, 2008). Scientific evidence suggests that poverty is associated with vulnerability for neurocognitive development, mainly affecting the development of the prefrontal cortex (PFC) (Sheridan et al., 2012), which is strongly associated with EF. It is important to note that EFs are connected to the capacity for self-control, both cognitive and emotional. The preschool years are characterized by a gradual increase in the capacity for self-regulation, in accordance with this being a time period of great development of the PFC, including its connectivity within subregions of the PFC, specifically the ventromedial, orbitofrontal, and dorsolateral region. The dorsolateral PFC has high levels of connectivity with other cortical regions and is linked to the development of metacognition. In contrast, the medial PFC has greater connectivity with subcortical regions, in particular with the limbic system, related to emotional and social control functions (Spencer-Smith & Anderson, 2009). Brain development is not characterized by linear growth, but rather goes through phases of overgrowth and pruning. Brain development also does not occur simultaneously in the brain, and the dorsolateral prefrontal regions are some of the latest to mature. During brain development, these regions are influenced by both genetic and environmental factors (Tsujimoto, 2008). Early experiences are critical in neurodevelopment, and SES has been shown to influence the development of brain regions underlying EF. For example, the development of prefrontal regions linked to EF in children from lower SES backgrounds is slower than among children from middle or higher SES backgrounds (Noble et al., 2015). Furthermore, poverty in early development has also been linked to emotional regulation, although research on the neural mechanisms involved in this association is relatively recent (Kim et al., 2013).

With respect to school performance, several studies have presented evidence that the development of EF is a significant predictor of classroom behavior, school readiness, and academic achievement (Blair & Razza, 2007; Brock et al., 2009), and that EF predicts these outcomes more strongly than classical measures such as IQ, reading level, or mathematical skills (Diamond et al., 2007; Razza, Martin, & Brooks-Gunn, 2012). It has also been suggested that adaptation to the school environment is linked more strongly to self-regulation than to knowledge of curricular content (Rimm-Kaufman, Pianta, & Cox, 2000). As well, inhibitory control, a core EF skill, is associated with prosocial behavior, emotional regulation, the capacity for teamwork, and research indicates that its development prevents the appearance of disruptive behaviors (Bierman et al., 2009; Brock et al., 2009; Ferrier, Bassett, & Denham, 2014).

Early childhood as a window of opportunity

In this chapter we refer to early childhood as the period between the prenatal phase and the transition to primary schooling, constituting a crucial period of development for every child (Anderson et al., 2003). From a neurobiological perspective, the high level of brain plasticity of children places early childhood development as a focus for human development policies (Shonkoff et al., 2000). In this sense, early childhood is considered a window of opportunity for the design of interventions for reducing the impact of developmental impacts that may persist throughout the life cycle. Likewise, early childhood is considered a time period when actions to amend the consequences of structural inequalities in our society would be highly cost-effective (Heckman, Stixrud, & Urzua, 2006).

In terms of cognitive and emotional development, early childhood can also be considered a sensitive period for the development of EF and the underlying brain structures. While the primary sensory regions mature early in development, maturation around the first year of life notably affects the PFC. For example, dendritic spines of pyramidal neurons in layer III develop up to the adult level, promoting the development of local circuits and reciprocal connections with other brain areas, which is accompanied by an increase in the frontal region's metabolism between 8 and 12 months of age (Koenderink, Uylings, & Mrzljak, 1994). In addition, at the behavioral level, improvements related to working memory and inhibitory control proceesses are observed. For example, in the "A-not-B" task, an object is hidden in front of the child's eyes, first in a place "A" and then in a different place ("B"), to explore the emergence and development of information retention during the delay interval (i.e., working memory) and the inhibitory control to avoid perseverance in the place search ("A"). At the neural level, the improvement in performance on this type of task has been linked to connectivity between frontal and parietal regions (Fox & Bell, 1990).

Between two and five years of age, brain metabolic consumption increases up to 2.5 times that observed in adults due to the energy demands of development. During this period, synaptic growth and dendritic arborization are at their greatest expansion (Casey et al., 2005). Cognitive improvements also occur in working memory and inhibitory control processes. Around age four, cognitive flexibility processes begin to emerge, associated with the ability to alternate between different rules and creative adaptation to the environment (Hernández, Carboni, & Capilla, 2012). As mentioned above, based on that core EF skill, other higher-order EF functions will develop along with the processes of emotional regulation.

Neural and cognitive development trajectories during early childhood depend on bidirectional interactions between biological and environmental aspects. In this sense, the home, childcare facilities, and educational centers, framed in broader sociocultural networks, provide highly relevant experiences for neural and cognitive development. Parental styles (Hughes, Devine, & Wang, 2017), cognitive training (Walker et al., 2005), and SES (Noble, McCandliss, & Farah, 2007) consistitute some of the primary variables that influence neurodevelopment in these early years.

The effects of poverty during this developmental period have also been widely described. For example, children from lower SES backgrounds tend to make more perseverative errors and have fewer consecutive correct answers in the "A-not-B" task, compared to peers from more favorable socioeconomic backgrounds (Lipina et al., 2005). Likewise, it has been found that children from lower SES backgrounds have on average reduced development of the brain surface area in regions supporting EF (Noble et al., 2015) and are more likely to have a differential electroencephalographic pattern in comparison with children from medium and higher SES backgrounds (Otero, 1997; Otero et al., 2003; Stevens, Lauinger, & Neville, 2009). Children growing up in vulnerable households are more likely to be exposed to stress, nutritional deficiencies, toxic agents, and lack of educational resources that could affect their brain maturation (Hackman, Farah, & Meaney, 2010; Noble, McCandliss, & Farah, 2007). In such a context, early childhood is an ideal window to provide experiences that might enrich developmental contexts and support environments that promote opportunities for cognitive and emotional development.

Interventions

Research in cognitive neuroscience has shown that EFs improve with practice and experience, and that these changes also produce modifications in the underlying neural networks (Posner & Raichle, 1994). Therefore, a systematic and specific early intervention that stimulates these EFs could be a tool that contributes to reducing the effects of socioeconomic disparities and to more equal opportunities for cognitive development (Flook et al., 2010; Karbach & Kray, 2009; Lakes & Hoyt, 2004).

During the last decade, several interventions have been designed to promote the development of EFs in young children, aimed at optimizing academic performance and social inclusion (Burger, 2010; Diamond & Lee, 2011; Lipina & Colombo, 2009). While some interventions are based on the use of electronic devices, such as personal computers and tablets, others rely on teacher-child interactions (Diamond et al., 2007; Segretin et al., 2014). Results of such studies suggest that interventions aimed to EF development in contexts of social interaction can promote or motivate self-control strategies in children (Diamond & Lee, 2011).

An experience from Uruguay

Inequality is one of the main afflictions in Latin American societies and has considerable costs. In particular, inequality increases poverty levels and reduces the impact that economic development can have on reducing it. Despite Uruguay being one of the Latin American countries with the lowest inequality index, the incidence of poverty continues to be alarming. According to the National Statistics Institute 9.7% of the population is below the poverty line. However, the situation deserves particular attention when considering the distribution by age groups, since the incidence of poverty is considerably higher in younger generations. This is the case for children under the age of 6 years, whose poverty level reaches 20.4% (INE, 2014).

In 2016, a team of researchers from the Center for Basic Research in Psychology (CIBPS [Centro de Investigación Básico en Psicología]) from the University of the Republic in Uruguay, in collaboration with researchers from the University of Buenos Aires, the University Torcuato Di Tella, and the Applied Neurobiology Unit in Argentina, started a research project focused on the study of cognitive development in early childhood in contexts of socioeconomic vulnerability. The project was financed with funds from the Social Inclusion of the Sectoral Commision for Scientific Research (CSIC, UdelaR [Inclusión Social de la Comisión Sectorial de Investigación Científica]). The specific aims proposed included: (1) to assess the impact of the socioeconomic context on the development of EFs; (2) to implement a cognitive intervention program; and (3) to evaluate the program effectiveness.

This research was possible thanks to the technical resources provided by the CEIBAL[11] platform in our country, which is the national version of the program "*One Laptop per Child*" [12] and is 100% implemented. Through this program, a computer or tablet is delivered to each child in the public education system in Uruguay, and internet connectivity is provided in all educational centers. This possibility allowed the adaptation of Matemarote, a digital platform for cognitive training for kindergarten children (Goldin et al., 2013, 2014; Lopez-Rosenfeld et al., 2013), in order to be used through CEIBAL devices for the cognitive assessment and training.

During 2016, the program was implemented in four public educational centers in Montevideo for 10-11 weeks. Centers

[11] www.ceibal.edu.uy

[12] http://one.laptop.org/

categorized as Quintile 1 (i.e., low SES) and Quintile 5 (i.e., high SES) by the Educational Monitor of the National Administration of Public Education (ANEP, 2012) were selected. A total of 12 evaluators (psychologists or advanced psychology students) and two coordinators (doctoral students) participated in the study, which allowed an approximate rate of 3-4 children per adult.[13]

Research design

An experimental design was implemented in which three phases were proposed: (1) child cognitive performance assessment (task carried out in the first week); (2) random assignment of each child to the study groups: intervention (activities: Matemarote platform) or control (activities: digital games with low demands for EF), and implementation of training activities three times a week for two months; and (3) evaluation of impact intervention (Figure 2).

[13] All the procedures involved in the project adhered to the ethical principles established in relation to the care and respect of child rights, and were evaluated and approved by the Ethics Committee of the Faculty of Psychology of the UdelaR. This implies the implementation of informed consent for parents, after describing the general aspects of the research, information on the use and confidentiality of the data, the characteristics of the experimental tasks, the duration of the project, and contact information. Once the parents received the information, meetings were held in each education center where questions were answered and the project was explained again. Only the children whose parents signed the consent participated in the research. Additionally, the research was explained to each child to describe in terms understandable for their age, and children were explicitly asked if they wanted to participate. Only children who expressed this desire participated in the study.

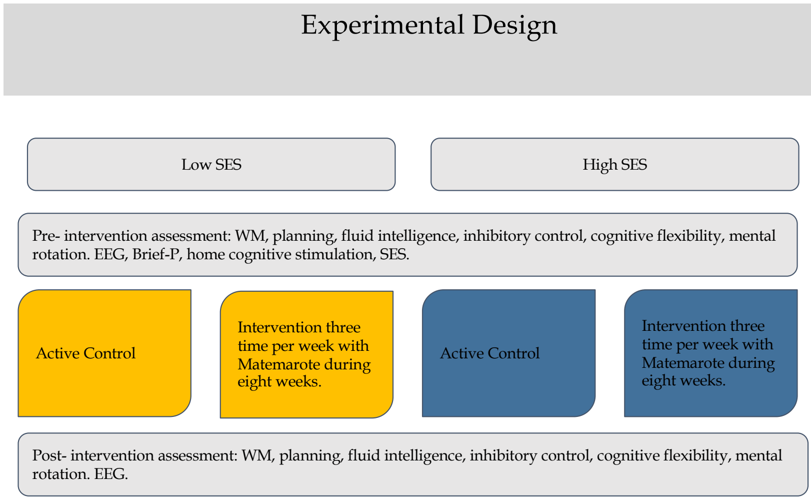

Figure 2 - Experimental design. Schools were selected according to the sociocultural context index (SCI), used by the Primary Education Monitor in the survey of sociocultural characteristics of public schools (ANEP, 2012). The yellow color represents Quintile 1 and the blue represents Quintile 5.

The instruments used for the pre and post-intervention assessments were the following:

(a) General intelligence meassure: Non-verbal Intelligence Test (Brown, Sherbenou, & Johnsen, 1982), designed to evaluate fluid processing in children. It is a 45-question matrix test that measures the ability to solve reasoning problems with abstract visual stimuli that increase in difficulty. Children must choose from different options the one that best completes the logical sequence.

(b) Inhibitory control and cognitive flexibility measure: Flower-heart type task adapted for preschoolers (Diamond et al., 2007). Participants' task is to press one of two buttons according to the shape that appears on the screen and its location. In each game, there are two possible shapes and two possible locations. The complete task includes three phases through which the

presentation conditions of the stimulus type change, progressively increasing the difficulty of the demands for inhibitory control. The last phase, in addition, adds the component of cognitive flexibility. Specifically, the three phases are: (1) congruent phase, which consists of the presentation of twelve trials in which only one shape appears (e.g., heart) and the instruction is to press the button on the same side that it appears; (2) incongruent phase, in which twelve trials are presented and a shape different from that of the previous phase appears (e.g., flower), with the instruction to press the button on the opposite side to the one that appears; and (3) mixed phase, in which congruent and incongruent stimuli are combined. The latter phase consists of twenty-four trials in which one or the other shape may appear and the instruction is to press the button on the opposite side -if the flower appears- or the one on the same side -if the heart appears.

(c) Planning measure: An adaptation of a Tower of London type task (Shallice, 1982) that evaluates planning processes of actions and representations, as well as spatial working memory, that contribute to the generation of a strategy to achieve a plan. Given an initial configuration of ball locations the children must reach another configuration of the final model in a limited number of movements and respecting the following rules: they can only move one ball at a time and can never have more than one ball in movement. The game gradually increases its level of difficulty.

(d) Visuoespatial working memory measure: Adaptation of the Corsi Blocks task (Corsi, 1972) that evaluates visuospatial working memory processes. In this task, the children have to reproduce a sequence of stimuli (lights that come on sequentially in a matrix). As the tests progress, the number of elements to retain and reproduce increases and also its spatial complexity.

(e) Visual rotation measure: Adaptation of the "Ghosts" task (Frick, Hansen, & Newcombe, 2013) developed to assess mental rotation

skills. In this task, children must select, from a pair of asymmetrical figures (ghosts) that appear in different orientations, the one that conforms to the shape shown in black at the top of the screen (i.e., model).

Cognitive training games

For the cognitive training the following games were selected and adapted for children of level five of initial education (Figure 3).

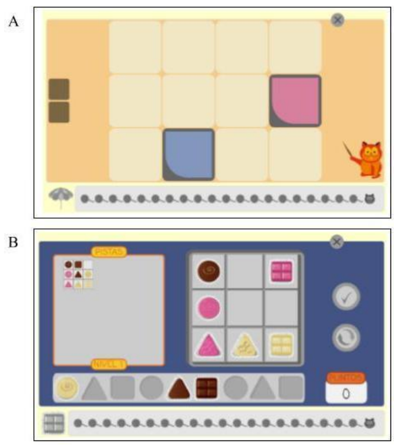

Figure 3 - Screenshot of two training games of the Matemarote platform: (A) "Memomarote"; (B) "Chocolate Factory".

a) Aircraft (inhibitory control and cognitive flexibility): This game was designed for inhibitory control and cognitive flexibility stimulation. Children should respond as quickly as possible within an allotted time, in which direction an airplane flies in the congruent condition (when the airplane appears yellow) and in the inconsistent condition (when the airplane appears red). This last condition presents greater difficulty since it requires suppressing an automatic response (same side) to offer a non-dominant response (the other side), and consequently requires greater inhibitory control. In other words, inhibitory control processes are mainly involved. Subsequently, the yellow and red planes will appear interleaved and children must alternate between the rules that apply to each color (with the yellow plane one must indicate where the plane is flying, with the red plane one must point to the opposite side). This condition demands cognitive flexibility since it is necessary to change the rule between trials and apply the rule corresponding to each trial based on airplane color, and thereby earn more points. At the end of the game the stimuli become more complex since the planes can appear inverted ("turned") and in this case the opposite rule must be applied to the one learned, which implies demands for reverse learning. In addition, other distracting elements are added to the screen, increasing the demands for inhibition of irrelevant information, and the targeted response times become shorter.

(b) Memomarote (working memory): This game is based on a self-ordered pointing task (Petrides & Milner, 1982). A set of elements is shown on each screen, and once any one of them is selected, the stimuli disappear and are relocated. The location of each item varies randomly each time a new one is selected, and children should point to a different item each time without repeating the ones they have previously selected. Advancing each level of play requires the children to execute a sequence of responses, remember it, and monitor their performance. At the initial levels with few elements, children can try to remember which elements they have already selected or which ones they lack to select, but as the game progresses and the difficulty increases (more elements to remember), children must develop another strategy (e.g., organized or cluster). The number of items to remember increases according to the child's performance.

(c) Chocolate Factory (logical reasoning): Adapted from the box game Chocolate Fix® from Think Fun Inc®, each screen shows a 3x3 position board with some pieces missing. The children must place the missing pieces according to their attributes and the clues

that are provided. In the simplest levels, the number of pieces to place is low and the information contained in the tracks is high. As the game progresses, the difficulty increases either because the number of tiles to place increases, the information provided to solve the problem decreases, partial clues (indicating only the color or shape of the piece) are incorporated, or a combination of these elements.

Results

Associations between socioeconomic context and EF performance

Results presented in this chapter are preliminary and based on the data collected with the sample of children from 2016, which corresponds to four kindergarten centers with a total of approximately 100 5-year-old children. Data suggest that the socioeconomic context is strongly associated with cognitive development. As can be seen in Figure 4, performance in the inhibitory control, cognitive flexibility, planning, and fluid intelligence tasks all exhibit significant differences between children who attend schools in Quintile 1 (lowest SES) versus schools in Quintile 5 (highest NSE). Performance of children in schools in the lower SES context is significantly lower.

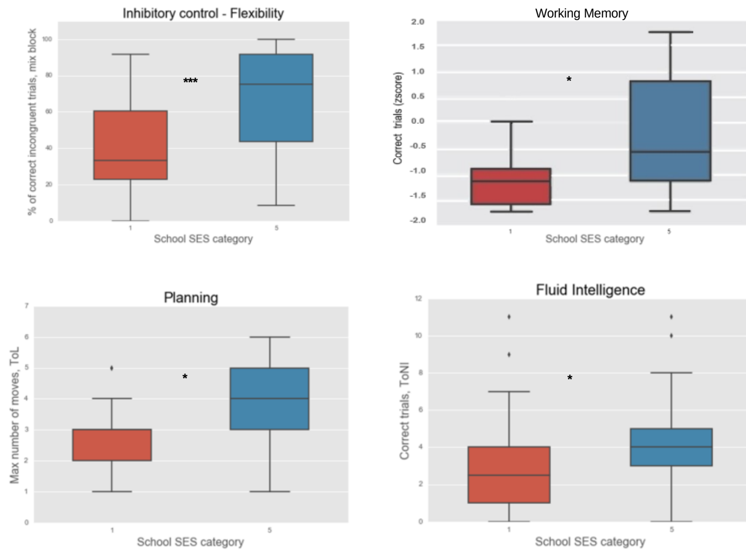

Figure 4 - Performance differences in inhibitory control, cognitive flexibility, planning, fluid intelligence and working memory tasks according to the school quintile. *Note*: * p-values< 0.01; *** p-values < 0.001.

Likewise, the association between SES and cognitive performance was also statistically significant (Figure 5).

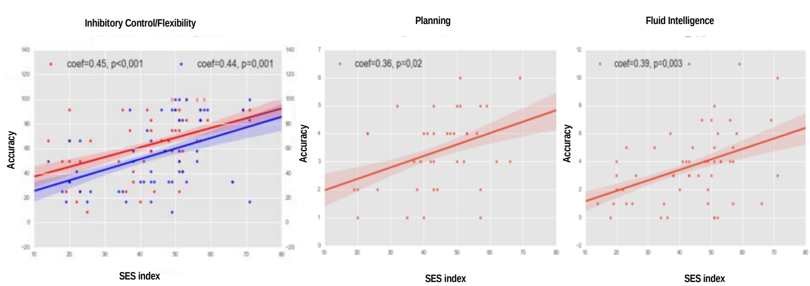

Figure 5 - Results of the association between SES and performance on tasks demanding inhibitory control and cognitive flexibility, planning and fluid intelligence. The red color in the first figure indicates the incongruent block (inhibitory control) and the blue indicates the mixed block (cognitive flexibility).

Specifically, the higher the SES index, the better the performance on tasks that evaluate inhibitory control, cognitive flexibility, planning, and fluid intelligence. However, no associations were found between SES and performance in the working memory task, nor between SES and performance on the mental rotation task (Figure 6) - for this latter task, no significant differences were observed by school quintile either.

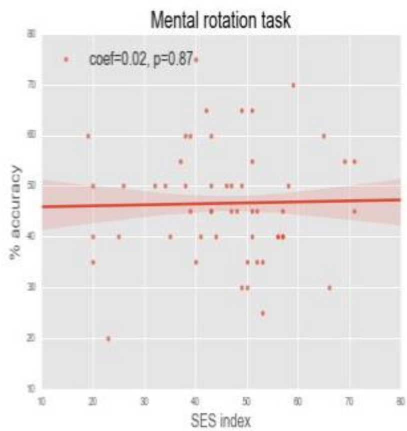

Figure 6 - Lack of association between SES and performance on mental rotation task.

Effects of the intervention on EF performance

Regarding results of the cognitive training, the preliminary results indicate that children belonging to the most vulnerable context (Quintile 1) performed significantly higher on inhibitory control and cognitive flexibility tasks after eight weeks of playing with the Matemarote platform. Specifically, children who had lower performances in the pre-intervention phase (that is, those who attended schools in Quintile 1) improved more after training (Figure 7).

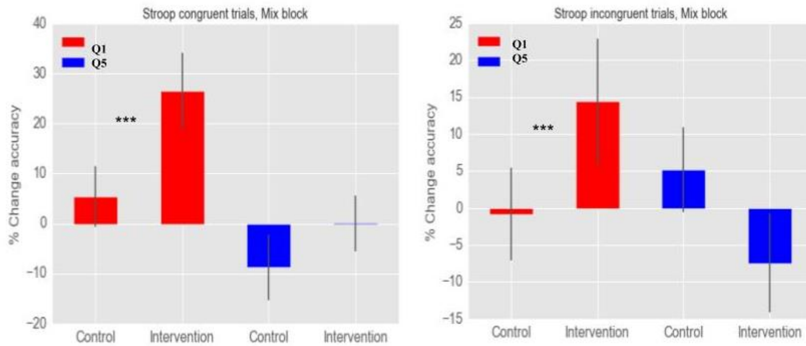

Figure 7 - Effect of the cognitive training games on the performance of inhibitory control and cognitive flexibility tasks. *Note*: * p-values< 0.01; *** p-values < 0.001.

Final conclusions and future perspectives

A central aspect of cognitive development in early childhood is the maturation of a set of mental abilities known as EF, which constitute a family of high-level cognitive processes that contribute to the regulation of behavior and emotions, concentration, manipulation and subsequent use of perceived information, and adjustment of actions to achieve specific goals. As mentioned, the development of EF is sensitive to the environment (Hackman, Farah, & Meaney, 2010), and, far from being static, it can be modified with practice (Diamond & Ling, 2016). However, the effects of cognitive training are still a matter of debate. For example, there is no consensus on the impact such training would have on other cognitive domains (transfer), or if the possible benefits are sustained in the long term (Diamond & Ling, 2016).

The main aim of this work was to contribute to the understanding of the association between poverty and neurodevelopment, and to generate strategies based on local data with the aim to equate opportunities for cognitive development. Data presented in this chapter support the hypothesis that socioeconomic context modulates developmental trajectories (i.e., association between SES and cognitive performance). However, the results are not similar for all cognitive processes evaluated, nor do they bear the same relationship with SES and the socio-cultural context of the school. For example, significant differences were found between children who attended centers in Quintiles 1 and 5 in the performance of tasks with demands for inhibitory control, cognitive flexibility, working memory, planning, and fluid intelligence, but not in the task of mental rotation. This result is in agreement with those of previous studies that point to EFs as cognitive processes that are more associated in their development with the socioeconomic context (Sheridan et al., 2012; Sarsour et al., 2011). In addition, a differential effect was observed in the performance of the working memory task between the educational context and the home. This result opens up the interesting possibility of thinking about school and home contexts, central scenarios for child development, that do not have the same associations with aspects of the EF development.

As was previously mentioned, these are preliminary results based on the characterization of the development context through a household SES index, which constitutes a reduction of more complex realities. To partially overcome this limitation, our data include other dimensions that will be incorporated into the final analysis of the sample: an approach to the SES from the perspective of the Unsatisfied Basic Needs poverty measure, home stimulation levels, and data of each child's brain activity. We hope that this larger set of data contributes to the understanding of the complexity of the interaction between context and neurodevelopment.

Our work also suggests that it is possible to positively influence performance in tasks with EF demands through the implementation of interventions that target them. Although the results are still preliminary, they support the notion that incorporating activities that promote the systematic and sustained use of cognitive skills is a strategy to promote development, particularly in those children who may not have a wide range of opportunities for stimulation in their developmental contexts. In addition, we also expect to contribute with a critical position regarding the negative effects of poverty on neurodevelopment, overcoming a language based on deficiencies and irreversibility. From this position, it is considered that children growing up in vulnerable contexts present a neurodevelopmental trajectory that is adaptive for the specific contingencies of their environment, allowing a functional adaptation in the short term, although it may be potentially harmful in the long term and in others environments, particularly the school one (Blair & Raver, 2012).

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PART III

Interdisciplinary frontiers

9

POVERTY AND ITS IMPACT: ENHANCING MECHANISTIC RESEARCH VIA A CROSS-SPECIES APPROACH

Rosemarie E. Perry

Introduction

Poverty is a global health concern and is even prevalent among affluent societies. For example, in the United States alone, 13% of the public live below the federal poverty line (Semega, Fontenot, & Kollar, 2017), which currently corresponds to an income of $25,100 for a family of four (U.S. Department of Health and Human Services, 2018). Incidence rates are even higher for children, with 1 out of every 5 children being born into poverty (Jiang, Granja, & Koball, 2017). Exposure to poverty in early life is associated with an increased risk of disparities in a multitude of important life outcomes, such as physical and mental health (Birnie et al., 2011; Cohen, Janicki-Deverts, Chen, & Matthews, 2010; Wadsworth, Evans, Grant, Carter, & Duffy, 2016; Yoshikawa, Aber, & Beardslee, 2012), life expectancy (Chetty et al., 2016), social-emotional and cognitive skills (Blair & Raver, 2016; Hackman & Farah, 2009; Noble, McCandliss, & Farah, 2007; Raizada & Kishiyama, 2010), and even brain development (Lipina & Posner, 2012). These disparities can persist throughout development, regardless of changes in socioeconomic status (Adler & Rehkopf, 2008; Poulton et al., 2002). Thus, reducing poverty and its effects is a matter of great public health importance, with poverty reduction ranking among the top goals of many governments and international consortiums.

Indeed, understanding and remediating the effects of poverty has remained a common goal of economists, sociologists, epidemiologists, psychologists, and neuroscientists. However, disentangling the causal effects of poverty on development is challenging due to the multidimensionality of poverty itself (Evans, 2004; Krieger, Williams, & Moss, 1997). In fact, poverty does not have a commonly agreed upon definition. Indicators of poverty have included a number of variables, ranging from household-level (e.g., family income, home chaos/crowding, material hardship, food insecurity, family instability, parental education, parenting quality) to community-level (e.g. community violence, neighborhood safety, access to health care and/or education), and also ecological (e.g. air and water pollution) and psychosocial (e.g., social inequality). To further complicate matters, while children growing up in poverty experience more frequent and cumulative exposure to adversities, these exposures in early life place a child at increased risk for developing poorer life outcomes independent of poverty (Amso & Lynn, 2017; Green et al., 2010). That is, stress-inducing adversities have a negative impact on child development regardless of socioeconomic status. This implies that it is not only exposure to poverty-related adversities, but also advantages that come along with wealth that is driving developmental disparities across the socioeconomic gradient (Amso & Lynn, 2017). Despite these challenges, it remains clear that gaining a better understanding of the components of socioeconomic status that have the most salient impact on child development is key to developing successful evidence-based interventions and policy implementations for families living at-risk. Such research is especially needed given that there is a current lack of treatments by which to enhance overall socioeconomic status, whereas policies targeting specific components of SES (e.g., income) can be more realistically enacted. However, there is a clear need for more rigorous techniques and novel approaches for teasing apart the complexity of poverty and mechanisms underlying its adverse effects across development. In this sense, in this chapter we will explore the usefulness of a cross-species program of research for the mechanistic assessment of poverty's effects on child development.

A mechanistic approach to poverty research

When it comes to understanding the mechanisms –or in other words, providing the "how"– by which poverty can influence development, human researchers face fundamental barriers to research. This is due to the simple fact that "mechanism" is a causal notion; one must have the ability to control and manipulate variables of interest in order to assess how an independent variable (e.g. indicator of poverty) causally affects dependent outcomes (Hedström & Ylikoski, 2010; Machamer, Darden, & Craver, 2000). Typically, the experimental control needed to determine cause-effect relations is achieved via a procedure referred to as random assignment, where participants are randomly placed into experimental vs. control groups. Random assignment ensures that each participant has the same opportunity to be assigned to any given group, thus increasing the likelihood that groups are the same at the outset of an experiment and eliminating the potential for observed results to be explained by anything other than the treatment of interest. While there are few instances in history where natural events have produced random assignment into or out of conditions of poverty (Costello, Compton, Keeler, & Angold, 2003; Rutter, 2003), by and large human researchers are fundamentally limited when it comes to directly assessing poverty-related mechanisms, due to necessary ethical constraints.

Human research has undoubtedly provided ample insight into potential mechanisms by which poverty might influence child development, by identifying meaningful associations and inferring causality between variables of interest through the use of sophisticated statistical modeling methods. However, simply put, human researchers cannot randomly assign families into or fully out of conditions of poverty. Without random assignment, researchers are predominantly limited to the collection of observational, correlational data. Although observational, correlational data does not provide direct mechanistic assessment of cause-effect relationships between poverty and developmental outcomes, importantly these data do account for the rich complexity of the human condition of poverty (e.g., cultural and psychosocial factors). In other words, human research has the advantage of high external validity, meaning results can be more readily generalized to situations and people external to the study itself. However, this high external validity comes as a trade-off to the research's internal validity; it's much harder for human research to establish true causal mechanisms by excluding or controlling for confounding variables.

Furthermore, human research faces technical and efficiency challenges when assessing the human brain and behavior across the lifespan. Despite the rise of sophisticated neural imaging and recording tools, researchers cannot directly test for neural mechanisms by which poverty might lead to altered developmental outcomes (Perry et al., 2018). Furthermore, due to the long lifespans of humans, researchers face efficiency challenges when studying longitudinal developmental research questions.

Together, the limitations faced by human researchers underscore the need for novel approaches, enabling a mechanistic research approach for studies exploring the impact of poverty on development. Applying a mechanistic approach would be valuable for a multitude of reasons. A mechanistic research approach would provide efficient discovery strategies for exploring conditions under which poverty-related adversity may or may not affect developmental outcomes of interest. Understanding these conditions is ultimately needed to inform strategies for maximally-effective, evidence-based change to be enacted via interventions and/or policymaking (Wight, Wimbush, Jepson, & Doi, 2016). Furthermore, understanding the underlying mechanisms at play, or in other words the "parts of the whole," allows for solutions to be crafted in accordance to the context, enabling multiple, individualized pathways for intervention (Findlay & Thagard, 2012). Additionally, looking across fields, it is clear that understanding mechanisms has historically lead to innovative solutions for complex problems, for example as has been the case for the treatment of phenylketonuria (PKU) (Diamond & Amso, 2008), peptic ulcers (Graham, 1993), and melanoma (Kudchadkar, Gonzalez, & Lewis, 2013). Lastly, thoroughly understanding the mechanisms by which interventions are operating can prevent unintentional harm/setbacks as a result of the intervention itself (e.g., antibiotic resistance crisis which has been attributed to the overuse and misuse of antibiotics (Ventola, 2015).

As researchers look to overcome limitations inherent to human studies regarding poverty and development and adopt a mechanistic research approach, the integration of animal models is an appealing solution (Perry et al., 2018). Animal research provides researchers with a high level of environmental control and the ability to manipulate variables, allowing for controlled studies of cause-effect relationships between variables of interest. Furthermore, advanced neuroscience techniques commonly employed in animal research enables researchers to go beyond identifying neural correlates related to poverty and development, by allowing exploration of neural mechanisms by which poverty-related adversity directly impacts areas of development. Importantly, understanding neurobiological mechanisms would enable highly sensitive measures which could be used for detection of the impact of poverty-related adversity on brain development, the creation of interventions, and the assessment of the efficacy of interventions. Additionally, animal models, and in particular rodent models, afford researchers with a more efficient option for studying longitudinal and multigenerational research questions, due to these species' rapid maturation, reduced lifespans, and ability to reproduce quickly. While animal models cannot encompass the complexity of human behaviors and the human condition of poverty, animals remain strikingly genetically (Gibbs et al., 2004) and biologically similar to humans, including within the brain (Buzsaki, Logothetis, & Singer, 2013).

Overall, the limitations of human research studies on poverty and development are the strengths of animal research, and vice versa: animal research faces advantages in terms of high experimental control, and thus high internal validity, but disadvantages when it comes to external validity. It takes many more steps to establish if findings from animal models are generalizable to human populations. Human research faces advantages in terms of high external validity, but disadvantages when it comes to internal validity.

In light of the strengths and limitations held by both human and animal research when it comes to studying poverty and child development, the author's program of research promotes the collaborative and integrative use of both human studies and animal models, within a bidirectional translational framework for developmental research, to advance translational research in a meaningful and efficient way (Perry et al., 2018) (Figure 1).

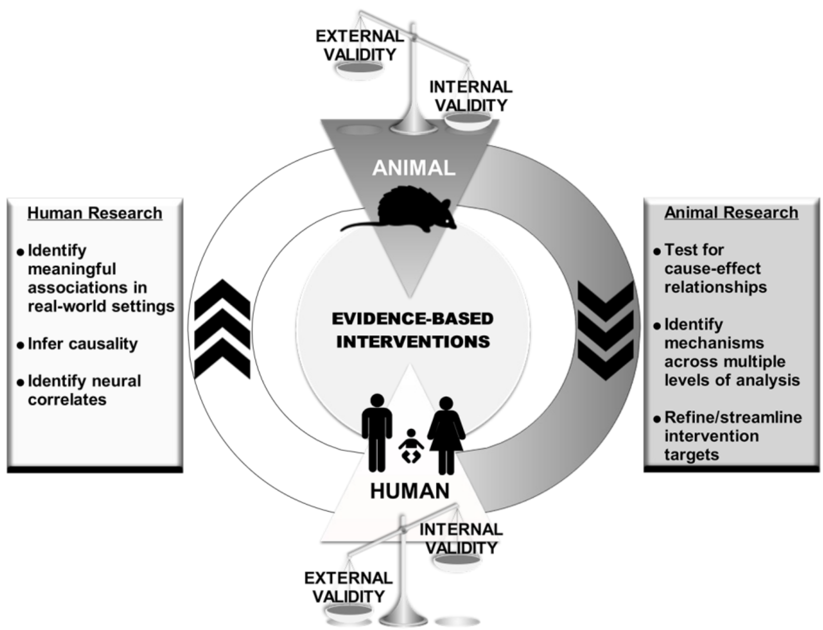

Figure 1 - A mechanistic, cross-species research approach. An integrative cross-species research approach provides solutions to current limitations faced by poverty researchers. While human studies provide important and meaningful results in real world settings (high external validity), they predominantly cannot go beyond inferring causality to establish causal mechanisms by which poverty impacts child development (lower internal validity). Animal studies have the advantage of high internal validity and can thus take important real-world observations "back to the laboratory bench" to test causal hypotheses and identify mechanisms by which poverty influences development.

However, given their lower external validity, animal studies rely on human studies to increase the translational relevancy of a study's design and findings. In turn, animal studies can provide mechanism-based focus to human studies, leading to the identification or enhanced specificity of targets for intervention. This iterative, bidirectional flow and refinement of findings between human and animal studies can increase the rapidity by which evidence-based interventions are created and scaled, and the efficacy and specificity of the interventions themselves.

By conducting concurrent cross-species research examining poverty-related adversity and its effects on developmental outcomes, one is able to embrace a mechanistic research approach, while maximizing both the internal and external validity of their studies. Furthermore, the use of a bidirectional, translational cross-species research approach provides an innovative solution to current limitations faced by developmental researchers. The inclusion of animal research allows human researchers to go beyond the assessment of correlation to assess causation at multiple levels of analysis (e.g., behavioral and neurobiological), and to conduct longitudinal research with greater efficiency. Additionally, animal models provide researchers with the ability to model and study the effects of distinct domains or aspects of poverty independently, such as resource depletion, home crowding, or exposure to pollutants, etc. (Evans, 2004). Conversely, the inclusion of human research allows animal researchers to encompass the complexity of human behaviors and the multifaceted condition of poverty, in order to maximize the ecological validity and translational potential of their study.

It is important to note that the bidirectional flow and continued refinement of findings between human and animal studies can enhance the rapidity and sensitivity by which interventions are created and scaled (Figure 1). Human studies provide important and meaningful results in real world settings. In turn, animal studies can take important real-world observations "back to the bench" to test causal hypotheses. Such animal studies can then provide focus to human studies, such as through the identification of particularly salient aspects of poverty on child development, or the identification of brain regions that are particularly sensitive to the effects of poverty-related adversity. This bidirectional, iterative cross-species approach has the potential to progress this area of research with surprising rapidity. This has been the case in the field of medical sciences, where a strong interface between human and animal research has resulted in numerous medical breakthroughs. For example, cross-species translational research has led to rapid development of treatments for HIV/AIDS (Deeks et al., 2012), cancer (Sagiv-Barfi et al., 2018), and vaccinations (Plotkin, 2014). A cross-species approach holds the potential to provide similar breakthroughs in social sciences, such as the field of child development.

A rodent model of poverty-related adversity

Perry and colleagues (2018) published a seminal paper utilizing a cross-species approach for the study of poverty-related adversity and child development (Perry et al., 2018). In this paper, data were presented from a rodent model of poverty-related adversity, in conjunction with findings from the *Family Life Project*[14], a prospective longitudinal study of 1,292 families, who were predominantly living below the federal poverty threshold (Vernon-Feagans & Cox, 2013). Using this cross-species approach, the authors asked if poverty-related adversity impacts the development of very young infants similarly in humans and rodents, and if parenting behavior is one potential mechanism by which poverty influences development. This paper was the first to attempt to

[14] https://flp.fpg.unc.edu/ (Editor's reference).

validate a rodent model of poverty-related adversity against human findings related to poverty and development.

In order to model a single facet of the human condition of poverty using a rodent model, the authors took a domain-specific approach to modeling poverty by creating conditions of resource depletion, or "scarcity-adversity." Under conditions of scarcity-adversity, a rat mother and her young offspring were provided with insufficient nesting materials within their home cage. These nesting materials, which in this case were wood shavings, are typically used by the mother rat to build a nest for her young infant rat pups, serving as the center for caregiving and a secure base for the pups. While other laboratories have used a similar rodent model of resource depletion (Walker et al., 2017), such models have predominantly been utilized for the study of early-life stress or abuse, rather than poverty-related adversity.

Perry and colleagues (2018) randomly assigned rodent mothers and offspring into conditions of scarcity-adversity or control conditions. In control conditions, a mother was provided with ample wood shavings materials, so that she had the available resources for nest building. Following 5 days of exposure to scarcity-adversity vs. control rearing conditions, pups were tested for developmental differences in infancy, using rodent-specific early-life indicators of social-emotional and cognitive developmental competence. These assessments of early-life developmental competence were reliant on infant responses to odor and somatosensory cues, as infant pups are born blind and deaf, and remain so until around postnatal day 15 when infant auditory and visual systems begin to emerge (Ehret, 1976; Weber & Olsson, 2008). Specifically, odor and somatosensory cues from the mother were used, as pups rely on these cues for survival in very early life (Hill & Almli, 1981; Hofer, Shair, & Singh, 1976).

Random assignment into scarcity-adversity rearing conditions directly impacted infant development, relative to control conditions. Pups reared in scarcity-adversity conditions showed a reduced preference to maternal odor, as indicated by approach responses in a Y-maze test, relative to control pups. Additionally, scarcity-adversity reared pups showed an increased latency to nipple attach to a mother, and an overall reduction in time spent nipple attached to an anesthetized mother in a maternal odor-guided nipple attachment test, relative to control reared pups. Lastly, maternal presence which typically regulates infant reactivity in times of distress (Hofer, 1996), did not reduce the infant distress calls (30-60 kHz ultrasonic vocalizations) of scarcity-adversity pups as much as control pups.

These scarcity-adversity induced disparities in very early life indicators of development competence were further underscored by neurobiological findings that scarcity-adversity reared pups have a unique neural network response to maternal odor. Through the use of 14C-labeled 2-deoxyglucose autoradiography (an indicator of neural activity), infant brain network functional connectivity was assessed in response to maternal odor presentations to awake, behaving pups. While control pup brains demonstrated a simplistic, organized network response to maternal odor, characterized by functional connectivity between the amygdala and hippocampus, in scarcity-adversity rats widespread differences were found. Scarcity-adversity exposed pup brains demonstrated extensive network functional connectivity between the olfactory cortex and areas of the limbic system in response to maternal odor, with particularly significant functional connectivity between the anterior piriform cortex and prefrontal cortex. Thus, scarcity-adversity exposure was associated with significant disruptions to circuit-level brain function, as early as in infancy, which may produce enduring development consequences (Di Martino et al., 2013; Scheinost et al., 2016). Further research is needed to elucidate neural mechanisms by which altered functional connectivity between brain regions might lead to developmental consequences as a result of poverty-related adversity.

Results from this experiment also demonstrated that the manipulation of home cage resource levels directly influenced the quality of rodent caregiving that pups received. Specifically, assignment into conditions of scarcity-adversity caused a reduction of observed maternal behaviors that are indicative of sensitive caregiving (Rilling & Young, 2014), relative to maternal behaviors in control conditions. For example, mothers living in conditions of scarcity-adversity demonstrated decreased time in the nest with their pups and nursing their pups. Furthermore, scarcity-adversity conditions caused an increase of observed behaviors that are indicative of negative caregiving (Drury, Sanchez, & Gonzalez, 2016): mothers in scarcity-adversity conditions began roughly transporting their pups (e.g., carrying by hind limb), stepping on pups, and scattering pups throughout the home cage.

When results from this rodent model of scarcity-adversity were considered in relation to findings from the Family Life Project, there were over-arching similarities between humans and rodents in regard to relations between poverty-related adversity, parenting, and infant development. Results from the Family Life Project mirrored findings from the rodent model of scarcity-adversity. Specifically, poverty-related adversity exposure was negatively associated with observed sensitive parenting behaviors and positively associated with negative parenting behaviors, with parenting fully mediating the association of poverty-related risk with infant affective and cognitive developmental competence (Perry et al., 2018). Thus, taken together, these cross-species findings dovetail to provide evidence that poverty-related adversity impacts multiple facets of infant development, even in very early life. Furthermore, these findings suggest process similarities in how poverty might influence infant development – via altered parenting behaviors. These similarities provide translational validity to this rodent model of scarcity-adversity, which should be further leveraged for discovering mechanisms (across multiple levels of analysis) by which poverty influences development.

Challenges and limitations

While the utilization of a cross-species mechanistic research approach will undoubtedly increase the scientific rigor and translational potential of poverty-related developmental research, widespread adoption of this approach requires overcoming substantial disciplinary, organizational, and scientific barriers. Foremost, most researchers hold expertise in either human or animal research techniques, but not both. To receive interdisciplinary training –while possible– would require a substantial increase in time and effort, which is not always desired nor feasible given the lack of interdisciplinary training programs. Therefore, successful cross-species programs of research are more attainably achieved via multidisciplinary collaborations, where researchers from different disciplines work together toward a common goal. The success of multidisciplinary collaborations rely upon overcoming both organizational and scientific boundaries (Cummings & Kiesler, 2005). Despite these challenges and limitations, there are a number of straightforward methods by which to foster cross-species mechanistic research. For example, on an organizational level, increasing the proximity of researchers and providing facilities that promote chance meetings encourages communication between researchers with different expertise, and has been shown to increase occurrences of collaborations (Balland, 2012). For institutes, this underscores the importance of situating laboratories of those working in common research areas (e.g., applied and basic developmental researchers) near one another. Centralizing cafeteria locations can also enhance chances of multidisciplinary collaborations. Furthermore, active attempts to dismantle the barriers to multidisciplinary communication can be made via the creation of interdisciplinary training tracks, and the inclusion of cross-departmental colloquia, seminars, and workshops within institutes (Bruun, Hukkinen, Huutoniemi, & Thompson Klein, 2005; Kraut, Galegher, & Egido, 1987).

Building bridges across disciplines can also be achieved via national and international multidisciplinary meetings and conferences. The XII International School on *Mind, Brain and Education* (MBE) on the "Neuroscience of Poverty," which took place at the Ettore Majorana Foundation and Centre for Scientific Culture in Erice, Sicily, is one such example. Here, researchers and experts from different disciplines and backgrounds came together for a week to discuss state-of-the-art research and innovate solutions to overcoming current barriers pertaining to the study of the neuroscience of poverty. This was achieved via academic presentations, distribution and discussion of participants' published and unpublished manuscripts, fruitful round-table discussions, and, perhaps most importantly, social bonding between participants of disparate fields. Discussions among participants quickly revealed that, organizational barriers aside, the integration of theories and methods from different disciplines into a new perspective is a challenge in and of itself. Thus, it became clear that in order to successfully integrate a cross-species mechanistic approach into poverty research, one must overcome significant scientific barriers (Bruun et al., 2005). For example, innovating solutions via a multidisciplinary approach can be easily stymied by a lack of familiarity that scientists tend to have with other disciplines, serving as a "knowledge barrier." Furthermore, there are oftentimes cultural barriers when looking across fields, such as workplace culture, and language-related use of specialized terminology, that must be reconciled for successful collaborations. Similarly, differences in techniques and approaches that are commonplace in different fields can lead to methodological barriers. Psychological barriers can also occur as a researcher is challenged to view their research beliefs and viewpoints from a new perspective, or even challenged to change their internalized attitudes and conceptualizations. Finally, reception barriers can arise when researchers are not understanding or receptive of the value that alternative fields and research approaches can provide.

MBE's "Neuroscience of Poverty" broke down these barriers by bringing together and educating experts from across the world and across disciplines. Knowledge barriers were challenged via socialization and transmission of knowledge between the school's participants. Furthermore, MBE participants discussed the need for a common language in poverty research, and decreased use of specialized terminology/jargon in publications and presentations. The use of accessible language would allow researchers to identify links across fields and increase opportunities for multidisciplinary collaboration. However, accessible and common language would also benefit the efforts of policy makers, community leaders, and the general public. Myriad methodological approaches were presented, discussed, and dissected, providing insight into how methodologies could be better integrated. For example, going beyond reporting statistical significance by also reporting effect sizes provides a common language for the interpretation of results, regardless of the methodological and analytic approach used. MBE participants were challenged to think about their research problems from novel perspectives, in the safe and productive environment of MBE. Participation in the MBE course in beautiful Erice also incentivized reception of information from alternative fields and approaches. While many were unfamiliar with mechanistic research approaches in poverty research at the start of the course, they soon learned of its value and potential to innovate and accelerate solutions.

In sum, promoting the use of mechanistic cross-species approach for the study of poverty requires overcoming substantial disciplinary, organizational, and scientific barriers. However, there are means by which this can be achieved (Klein & Newell, 1997). While institutional-level changes can promote effective cross-species research, researcher-level changes can further guide the process. Attendance and dissemination of research findings at multidisciplinary conferences and courses can enable transfer of knowledge and forge working multidisciplinary relationships. Reading across fields can further break down barriers to mechanistic research. Whether these efforts result in multidisciplinary collaborative programs of research, or an increase of research that is informed by fields outside of a researcher's own area of expertise, they are likely to lead to innovative research on poverty and development.

Conclusions and future directions

Growing up in poverty is associated with an increased risk of substantial disparities in cognitive and social-emotional development, physical and mental health, and achievement throughout the lifespan (Adler & Rehkopf, 2008; Bradley & Corwyn, 2002). While psychological, sociological, and epidemiological research approaches provide valuable insight into poverty and its impact, the integration of neuroscience research using animal models is needed to assess cause-and-effect relationships between poverty and developmental outcomes. The field of cross-species developmental research is nascent, however successful past examples have demonstrated the feasibility and high potential for impact of this approach (Casey et al., 2010; Cohen et al., 2013; Diamond & Amso, 2008; Pattwell et al., 2012; Perry et al., 2018; Warneken, Hare, Melis, Hanus, & Tomasello, 2007). Thus, future research on poverty and its impact on development should be informed by mechanistic research involving animal models, or directly incorporate mechanistic research through the use of a cross-species approach. Ideally, animal models would model one facet of poverty at a time (e.g., resource depletion, pollution exposure, nutrition, etc.), to help researchers begin to disentangle which aspects of impoverished environments have the most salient effects on child development. Such a mechanistic understanding will enable the design of more specific, powerful interventions for the prevention and remediation of the effects of poverty. Furthermore, animal models would ideally be used to disentangle how early-life adversity vs. early-life advantages impact development, as they are distinct domains to be considered when assessing the impact of socioeconomic status across the gradient (Amso & Lynn, 2017). Lastly, the use of animal models will be vital to elucidating neurobiological mechanisms by which poverty can influence development.

With the goal of rapidly maximizing the translational impact of studies, future research would ideally use an integrative, bidirectional cross-species approach, which provides solutions to current limitations faced by developmental researchers. However, there are considerable barriers to establishing interdisciplinary research of this kind (Klein & Newell, 1997). Overcoming such barriers will involve increased efforts of both institutions, and the researchers themselves. Furthermore, building bridges by assembling researchers working to solve common problems, as was achieved by the MBE "Neuroscience of Poverty" course, will pave the way for future interdisciplinary research programs and/or multidisciplinary collaborations. Ultimately, cross-species data can help facilitate and even enhance the process by which research is used to improve the lives of at-risk children.

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10

USING NEUROCOMPUTATIONAL MODELLING TO INVESTIGATE MECHANISMS UNDERLYING SOCIOECONOMIC STATUS EFFECTS ON COGNITIVE AND BRAIN DEVELOPMENT

Michael S. C. Thomas

Introduction

Poverty is about people's lives. Inequality, one of its major drivers, is a social issue. Cognitive neuroscientists have become increasingly interested in how being raised in poverty impacts children's brain and cognitive development. But how can it be useful to reduce people to instances of individual brain function? Poverty is the result of social structures and therefore a focus on neuroscience would appear to be a distraction (Farah, 2017).

There are at least three reasons why a cognitive neuroscience approach may be useful. First, as we shall see, socioeconomic status (SES) – typically measured by a combination of family income, parental occupation, and parental education – has been found to correlate with differences in brain structure, brain function, cognitive ability, and educational achievement. However, many factors co-occur with low SES (see, e.g., Hackman et al., 2015). Mothers may be more stressed, have poorer diets, and more drug exposure while pregnant; children may be raised in less nurturing, more polluted, and more dangerous environments; there may be less social or neighborhood support, poorer schools, and less supportive attitudes to education; children may have fewer resources and opportunities for cognitive stimulation and learning. This array of factors may not all be equally responsible for producing health, cognitive, and educational outcomes. If the biological causal pathways of SES effects are identified, this can help to target the most efficient interventions to alleviate the downstream effects of poverty. Such interventions offer short-term measures, while the longer-term social goal of reducing poverty can be pursued.

Second, there is a straightforward sense in which evidence that poverty affects the brain in measurable ways is a powerful message to policymakers. A brain image is worth a thousand words. Brain data, however, represent a double-edged sword, because policymakers may be liable to think that effects observed on brain structure and function are then immutable. They are not, because we know that the brain is plastic, and behavioral interventions can improve outcomes. A study of brain mechanisms must also, therefore, emphasise this message and seek to identify pathways to remediate observed deficits.

Third, work in education, the social sciences, and the cognitive sciences has generated a large body of empirical data on outcomes that are *correlated* with SES. But these correlational data are open to misunderstanding and misinterpretation if the underlying mechanisms are not understood. Here are three examples of empirical data and three respective possible interpretations.

(1) Gaps in children's IQs (cognitive ability) across levels of SES are evident from infancy and these gaps widen through childhood and adolescence (von Stumm & Plomin, 2015). *Some process must be getting worse across childhood to make the gaps widen.*

(2) When children are split into brighter and less bright groups around two years of age and then followed up, over time brighter children from poorer backgrounds fall back compared to their peers, and by age 10, they have been overtaken by less bright classmates from richer families (Feinstein, 2003). *With age, children's rank in their class is increasingly constrained by environmental factors such as SES*. From data like these, policymakers have concluded that early potential is lost through environmental factors such as poor childcare, poor early years education, poor schooling and lack of access to health services (HM Government, 2003).

(3) One way to measure social mobility is to assess whether children reach a higher level of educational attainment than their parents. On this measure, however, at least half the variability can be linked to genes (Ayorech et al., 2017). *Genetics would seem to place limits on how much social mobility can be influenced by interventions*. Do genes restrict whether children can escape poverty through education?

This chapter outlines one methodology within cognitive neuroscience to investigate the mechanisms underlying SES effects on brain and cognition: multi-level neurocomputational models of cognitive development. The model presented here was applied to each of the above empirical effects. It generated alternative interpretations of each set of empirical data (Thomas, Forrester & Ronald, 2013; Thomas et al., in preparation; Thomas & Meaburn, in preparation).

SES effects on brain and cognitive development

We begin with a (very) brief overview of the existing empirical literature. We know that differences in SES have marked effects on cognitive development (Farah et al., 2006). These effects are not uniform across all areas of cognition, but are particularly marked in the development of language and cognitive control (often referred to as 'executive functions'). Hackman and Farah (2009) considered these differential effects in terms of relatively independent, anatomically defined neurocognitive systems in the brain. The strongest effects of SES were observed for the language system (left perisylvian regions) and the executive system (prefrontal regions, decomposed into working memory system [lateral prefrontal], cognitive control [anterior cingulate] and reward processing [ventromedial prefrontal]). SES explained 32% of the variance in the language composite behavioural measure, 6% in cognitive control, and 6% in working memory.

Effects of SES have been observed on measures of brain structure using magnetic resonance imaging. For example, Noble et al. (2015) reported effects of family income levels on cortical surface area in a cross-sectional sample of 1099 children in the USA aged 3-20 years. The relationship was non-linear, with the strongest effects observed in the lowest income families; differences in income at higher levels were associated with smaller changes in cortical surface area. However, SES only explained a few percentage points of the variance; there was a great deal of variation in brain structure measures not explained by SES. Notably, the strongest effects of SES on brain structure were found in regions supporting language, reading, executive functions, and spatial skills, consistent with behavioural evidence.

SES has also been found to impact neural development at much earlier ages. Betancourt et al. (2016) examined the relationship between SES measures (income-to-needs ratio and maternal education) in a sample of African-American female infants aged 5 weeks. They observed that lower SES was associated with smaller cortical grey and deep grey matter volumes, pointing to the biological embedding of adversity very early in development.

The link between brain structure and function is indirect and not well understood. Nevertheless, researchers have observed differences in brain function associated with SES both with functional magnetic resonance imaging (regional oxygenated blood flow differences) and with electrophysiology (measurement of voltage potentials on the scalp associated with neural activity). For example, using functional magnetic resonance imaging, Raizada et al. (2008) found that the weaker language skills observed in 5-year-old children from lower SES backgrounds were associated with reduced hemispheric functional specialisation in left inferior frontal gyrus. Specialization to the left hemisphere is a marker of the functional maturation of language systems. Using electrophysiology with a sample of 3-8 year olds, Stevens, Lauinger, and Neville (2009) demonstrated reduced neural signatures of selective attention in children from lower-SES families (indexed by maternal education). In an auditory processing task where the children had to attend selectively to one of two simultaneously presented narrative stories, the neural processing differences that characterised the lower-SES children were related specifically to a reduced ability to filter out irrelevant information.

These few examples illustrate the general methods from a fast growing neuroscience literature (for wider reviews of structural and functional brain imaging and SES see Farah, 2017; Pavlakis et al., 2015). Importantly, cognitive neuroscientists do not yet understand the causal pathways of these cognitive and brain effects, not least because the SES measure represents a distal cause and does not isolate the proximal causes that influence cognitive and brain development. Some differences associated with low SES may represent *deficits* (e.g., poorer brain development caused prenatally by poor maternal nutrition or postnatally by chronic stress). Others may represent *adaptation*s (e.g., apparent poorer selective attention may reflect higher vigilance appropriate to a more dangerous environment; impulsivity may reflect maximising short-term rewards because long-term rewards have proved unreliable).

Hackman, Farah, and Meaney (2010) classed potential causal mechanisms into three types, based on naturalistic research with humans and experimental research with animal models: (1) those operating prenatally on fetal development, (2) those affecting postnatal parental nurturing, and (3) those affecting postnatal cognitive stimulation. Explanatory models tend to distinguish what is lost from lower SES families (resources, good nutrition, learning opportunities) from what is added (stress, toxins, childhood adversity experiences) (Sheridan & McLaughlin, 2016). Causal explanations are likely to be complex: all three classes of factors could be responsible, or combinations could differ per brain system. The combination of factors may depend on details of the specific population and local factors, in terms of absolute levels of resources/poverty, where the economic and environmental restrictions lie in a particular society, and the relative levels of poverty (inequality).

Against this background of (hopefully) remediable environmental effects, we also know that in Western societies, a fair proportion of children's variability in cognitive and educational outcomes, and indeed brain structure, can be predicted by their genotypes – that is, abilities are 'heritable' (Plomin et al., 2016). The term heritable is often misunderstood to relate to necessary outcomes (because children's genes aren't changeable) but this interpretation is incorrect. In different environments, genetic effects may be increased or decreased: observed genetic effects are not inevitable or deterministic. They show what is, not what can be. Nevertheless, we can take measures of heritability as current summary statistics: given the current range of family and educational environments that children are raised in, and which shape the world they can explore, heritability is a statistic that capture how much variance is currently being predicted by genetic similarity.

There has been a flurry of new findings with respect to life outcomes, SES and behavioural genetics. For example, researchers have reported that educational achievement is 'highly' heritable, with as much as 60% of the variance in examination results in 16 year olds explained by genetic similarity (Krapohl et al., 2014). These genetic effects appear general across topics rather than specific to different academic subjects (Rimfeld et al., 2015). Direct measures of DNA variation have pointed to regions of the genome associated with academic achievement, albeit with coarse educational measures as the outcome (years of schooling completed) and smaller amounts of variance explained (e.g., 11-13% variance; Lee et al., 2018). Notably, variations in SES have been reported to partly align with genetic variation (e.g., Trzaskowski et al., 2014). Moreover, social mobility – where an individual's SES differs from that of their parents, such as in educational attainment – has itself been reported as partly heritable, with one study observing that just under half of the variance in social mobility was linked to genetic variation (Ayorech et al., 2017), and another study reporting that direct measures of DNA variation could explain around 3% of the variance in upward educational mobility (Belsky et al., 2018).

Evidence of the role of genetic variation in influencing cognitive, educational, and life outcomes, and of the possible correlations between the genetic variation and SES gradients, drives the debate between *social causation* and *social selection* accounts (Farah, 2017). Under a social causation account, SES effects and their persistence across generations are driven by the environments in which children are raised. Under a social selection account, SES-related differences in brain and cognition are under genetic control, with population stratification of genotypes according to SES.

Our concern here is not the competing merits of these accounts, but merely the challenge posed by respective data on the roles of environmental factors and genetic factors on brain and cognitive development. How can these bodies of empirical data be reconciled into a coherent causal account? Given the complexity and multi-faceted nature of both brain development and cognitive development, how can we begin to formulate and test competing explanations for the pathways by which SES effects operate – and their implications for intervention? Even under a social causation account, one must accept the role of genetic variation in contributing to differences in outcomes. Even under a social selection account, one must accept that differences in experiences will influence development.

Neurocomputational modelling

One method used in cognitive neuroscience to formulate and test causal accounts is computational modelling. Models can be formulated at different levels of description: of individual neurons, of circuits of neurons, or of whole brain systems. In each of these cases, models seek to capture empirical evidence on patterns of brain activation or anatomical structure. Models can also be formulated at a cognitive level: although certain constraints may be included from neuroscience about the nature of computation, the target is then to capture empirical data on high-level behaviour. Multi-level models include constraints from several levels of description and seek to capture data both at the level of brain and behavior (Thomas, Forrester & Ronald, 2016). Models may be constructed to simulate the characteristics of the static properties of a system at a given point in time, or they may be constructed to capture developmental change, where trajectories of behavior are simulated as they alter over time (Elman et al., 1996; Mareschal & Thomas, 2007).

How might we construct a multi-level computational model to explain SES effects on brain and cognitive development? Minimally, we need to stipulate a neutrally constrained developmental mechanism which acquires a target behavior through interaction with a structured learning environment; we need to stipulate how growth of that developmental mechanism and interactions with the structured learning environment might alter as a consequence of variations in SES; and we need to stipulate separately how genetic variation might alter the properties of the developmental mechanism, for example in terms of how it grows, operates, and responds to stimulation. Thomas, Forrester, and Ronald (2013) began this line of research by constructing an artificial neural network model of the effects of variation in SES on language acquisition, focusing on the specific domain of inflectional morphology (that is, altering the sounds of words to change their meaning, such as in forming the past tense of a verb). The model was able to simulate how children's language skills altered across the SES gradient, as well as generating testable predictions about children's language outcomes (see also, Thomas & Knowland, 2014; Thomas, 2018, for the model's extension to considering delay and giftedness). Thomas, Forrester, and Ronald (2016) and Thomas (2016) showed how the same model, treated more abstractly, could be extended into a multi-level format, to incorporate a genetic level of description and indices of brain structure as well as behavior. In the following sections, we demonstrate how the model can be applied to considering SES effects on brain and cognitive development (Thomas et al., in preparation; Thomas & Meaburn, in preparation).

Model assumptions and simplifications

A schematic of the model is shown in Figure 1. In the model, cognitive development occurs through the interaction of an experience-dependent mechanism with a structured learning environment. The mechanism is an artificial neural network, which embodies computational constraints from neural processing (Elman et al., 1996). These constraints are, respectively, a network of simple non-linear integrate-and-fire processing units, distributed representations of knowledge, associative error-driven learning altering network connectivity strengths and unit thresholds, and network development including phases of growth and pruning. The structured learning environment is drawn from the field of language development. The single processing structure is assumed to lie within a larger cognitive architecture but is not intended in this model to correspond to any specific brain region.

The mechanism learns input-output mappings that drive behaviour relevant to its domain. Accuracy of input-output mappings is used as a measure of behavioral performance. Structural properties of the artificial neural network, including the total number of connections and the total strength of excitatory and inhibitory connections, are used as analogues of brain structure measures such as cortical thickness, cortical surface area, grey matter volume, and white matter volume (Thomas, 2016).

Individual differences factors, such as SES and genetic variation are not considered in isolation but in terms of how they modulate the above species-universal mechanisms that underpin development across all children. In this sense, the model construes individual differences as operating within a developmental framework (Karmiloff-Smith, 1998). Various options are available to implement the effect of SES: as a modulation of the level of stimulation available in the learning environment (see Thomas, Forrester, & Ronald, 2013); as a modulation of the growth of the network and its processing properties; or both of these effects operating in a correlated fashion (see Thomas et al., in preparation). Each network represents a simulated child undergoing development in a family environment. Each family is assigned a value, between 0 and 1, to represent its SES, which is then used to modulate the learning environment or the network structure.

Genetic variation is assumed to operate by influencing the neurocomputational properties of the processing mechanism, in terms of its capacity, plasticity, and noisiness of processing (these are broad characterisations of the role of a larger set of parameters, show in Table 1). Since behavioral genetic research on cognition has indicated that common genetic variation amounts to large numbers of small genetic effects on a wide range of neural properties, genetic variation is implemented via a polygenic coding scheme: an artificial genome contains sets of genes which each influence variation on a neurocomputational property (14 properties, each influenced by 8-10 genes); the combination of small variations across a large set of properties produces networks with a normal distribution of learning properties (Thomas, Forrester & Ronald, 2016, for details). The combination of simulated children with different learning abilities, interacting with environments with different levels of stimulation, produces a population of children with different developmental trajectories in both behavior and brain structure. At any point in development, cross-sections can be taken of behavior or structure across the population, and correlations derived to SES or genetic variation.

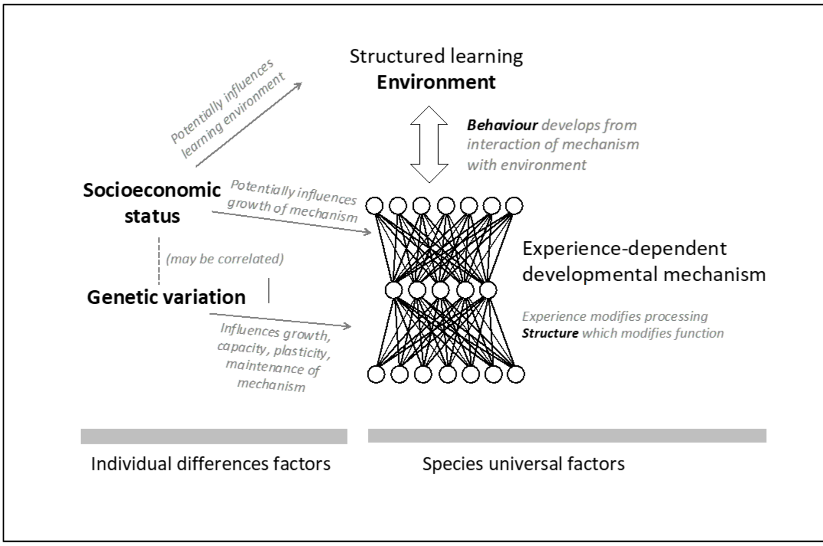


Figure 1 – Structure of neurocomputational model simulating SES effects on cognitive and brain development. An experience-dependent developmental mechanism (artificial neural network) interacts with a structured learning environment to acquire a cognitive behavior. The multi-level model embodies constraints at the level of genes, brain structure (connections, units), behavior, and environment. Individual differences factors (SES, genetic variation) are considered with respect to how they modulate species universal mechanisms supporting cognitive development.

Simulation design

A single network was trained on its family-specific set of input-output mappings. Per its source cognitive domain, in this case the inputs were phonological representations of verb stems and the outputs were inflected forms of English verbs. Lifespan development corresponded to 1000 exposures (or 'epochs') of the network to the training set. The training set comprised a maximum of 500 input-output mappings. The development of 1000 individual children was simulated. Genomes were randomly initialised to produce genetic variation in learning ability across the population. Pairs of 'twin' networks were created which either shared the same genome (identical) or shared 50% of genes on average (fraternal) and twin pairs raised in the same family. This design enabled the use of twin correlations to compute heritability levels. SES was allowed to vary widely across families to capture the potential effects of poverty. In the simulations described here, SES was implemented as modulation of the level of stimulation in the learning environment, and was allowed to vary between 0 and 1. A family with a value of 0.6 would generate a training set that only contained a (randomly sampled) subset of 60% of the full training set (see Thomas, 2016, for further details, including specification of neurocomputational properties and calibration of their range; results are reported for the G-wide E-wide condition in that paper).

Simulation 1: SES effects on IQ change across development

Thomas et al. (in preparation) first considered developmental trajectories of behaviour. The population was split into three groups, those in the upper quartile of SES (training sets with >75% of available experiences), those in the middle two quartiles, and those in the lowest quartile (<25% of available experiences). Figure 2(a) shows the latent growth trajectories of IQ for children from low, middle, and high SES groups in the empirical data of von Stumm and Plomin (2015), for around fifteen thousand UK children followed from infancy to adolescence. It shows diverging trajectories with age. The SES gap widens. Figure 2(b) shows simulated data of IQ scores in the model, where IQ was computed according to the population distribution at each measurement point [IQ score= ((individual performance – population mean)/population standard deviation X 15) + 100]. Figure 2(c) shows the developmental trajectories of performance without the transformation to IQ scores. The simulation is able to catch the lower initial levels of performance at the youngest age, as well as the divergence of the trajectories across developmental time.

One might conclude from the empirical data that the conditions producing SES differences in cognitive development must worsen over time to produce the divergence. The simulations reproduced the diverging pattern with a consistent SES effect over time. In the model, divergence occurred due to non-linear trajectories of development. Increasing gaps between SES groups do not, then, necessarily imply worsening SES causal factors.

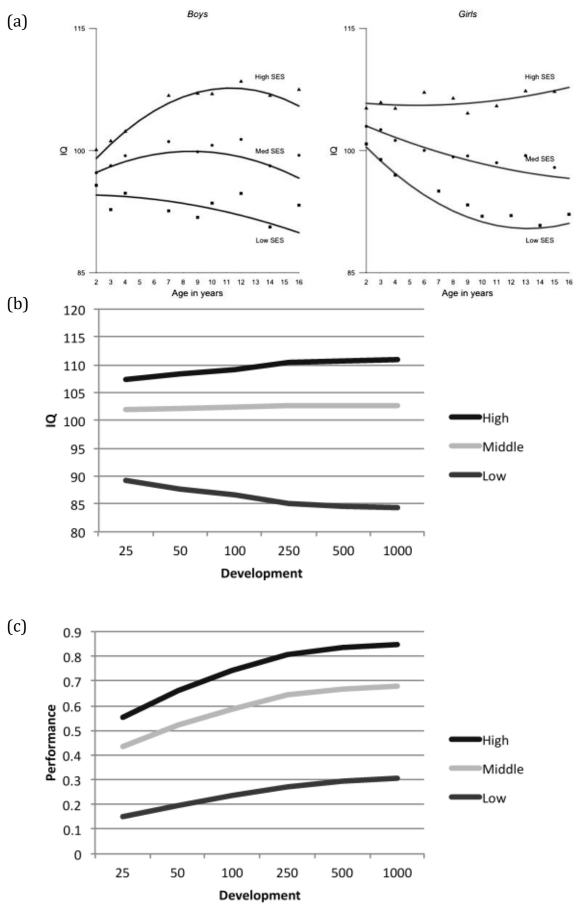


Figure 2 – (a) Empirical longitudinal data from a UK sample of twins (N= 14,853 children) plotting IQ change over development from infancy to adolescence, split by socioeconomic status and shown separately by gender (reproduced with permission from von Stumm & Plomin, 2015). High SES = > 1 standard deviation (SD) above SES mean; low = < 1 SD below SES mean; middle = < 1 SD above SES mean and > 1 SD below SES mean. (b) Simulation data plotting IQ change across children's development where SES is captured by differences in cognitive stimulation. High SES = upper quartile, Middle SES = middle two quartiles, Low SES = lower quartile. (c) Equivalent mean performance on task (proportion correct) for simulated SES groups.

Simulation 2: SES and developmental effects on population Rank order

Thomas and Meaburn (in preparation) used the same model to simulate the analysis reported by Feinstein (2003). The empirical data from the 1970 Birth Cohort Survey are re-plotted in Figure 3. Around 1,300 UK children were classified into high (upper quartile) and low (lower quartile) cognitive ability at 22 months and then followed longitudinally to 10 years of age, with high SES (top 24%) and low SES (bottom 13%) subgroups tracked separately. Children are depicted by the mean population rank order of their group, where 100 is high performance and 1 is low performance. Somewhere between 5 and 10 years of age, initially high-ability/low-SES children fell below the rank of low-ability/high-SES children. Following publication of these data, the findings were criticised on two grounds. First, that they do not represent a real effect but instead regression to the mean of initially extreme scores through measurement error (Jerrim & Vignoles, 2013). Second, that the most emotive finding, of the cross-over of high-ability/low-SES and low-ability/high-SES groups between 5 and 10, was hard to replicate and depended on cut-offs used to define groups; for example, crossing-over was more likely under less extreme definitions of high and low cognitive ability (Washbrook & Lee, 2015; e.g., Figure 1).

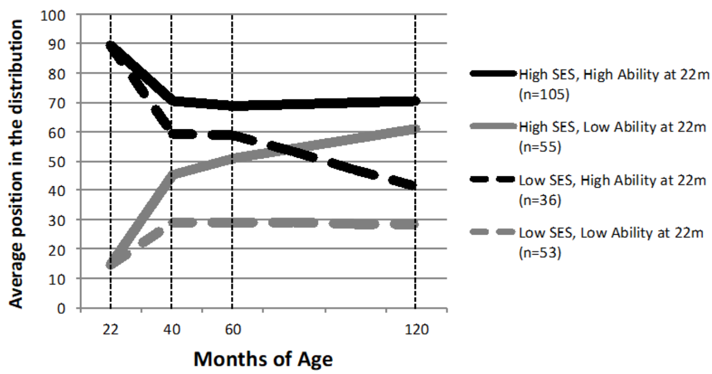


Figure 3 – Longitudinal empirical data from the 1970 Birth Cohort Survey following the population rank of children on cognitive ability tasks, split by ability (high, low) at 22 months, and family socioeconomic status (re-plotted from Feinstein, 2003). Y-axis shows mean population rank of each group, where a higher rank marks better performance on age-appropriate cognitive tests.

Figure 4 depicts the computational simulation of these data (Thomas & Meaburn, in preparation). Early in training (25 epochs out of 1000 epochs), simulated children were split into high and low 'ability' groups based on behavior (accuracy of input-output mappings). High ability was defined as population rank >650 (where 1000 is good, 1 is poor), low ability as population rank <350. These groups were subdivided by SES, as a mean split (simulated SES varied 0 to 1; high SES>.5, low SES<.5). Performance of the groups was then followed over development. Figure 4(a) depicts the mean population rank of each group. As in the Feinstein (2003) data, high-ability/high-SES and low-ability/low-SES groups broadly held their mean rank. High-ability/low-SES showed declining rank and low-ability/high-SES show ascending rank, such that the groups converged. Notably, they did not crossover. Figure 4(b) shows the same data but for performance. It is included to emphasise that we are observing modulations in developmental trajectories, and that changes in relative rank positions may exaggerate small differences in individuals who are nevertheless all showing developmental improvements with age.

Crucially here, there was no noise in the measurement of performance in the groups. The convergence of the trajectories, at least in the simulation, cannot have risen from regression to the mean following measurement error (Jerrim & Vignoles, 2013). It is a real reflection of the operation of constraints on development. Figure 4(c) takes the same population of children but now alters the definition of high and low ability to be less extreme (high ability: population rank >500; low ability: population rank <500) and the definition of SES more extreme (high: SES >.75; low: SES <.25). Now the trajectories of high-ability/low-SES and low-ability/high-SES did cross over. The simulations captured the empirical observation that the crossover pattern is sensitive to group definitions (Washbrook & Lee, 2015).

One simple interpretation of the Feinstein data is that changes in children's population rank performance in cognitive ability tests stem from environmental causes. For the simulation, we have available to us the full set of parameters that influences each simulated child's developmental trajectory: both the stipulated environmental effect, in terms of the level of cognitive stimulation, and the stipulated genetic individual differences, in terms of the neurocomputational patterns of each artificial neural network. We can then use these parameters in a multiple regression analysis to see which predicted population rank change across development.

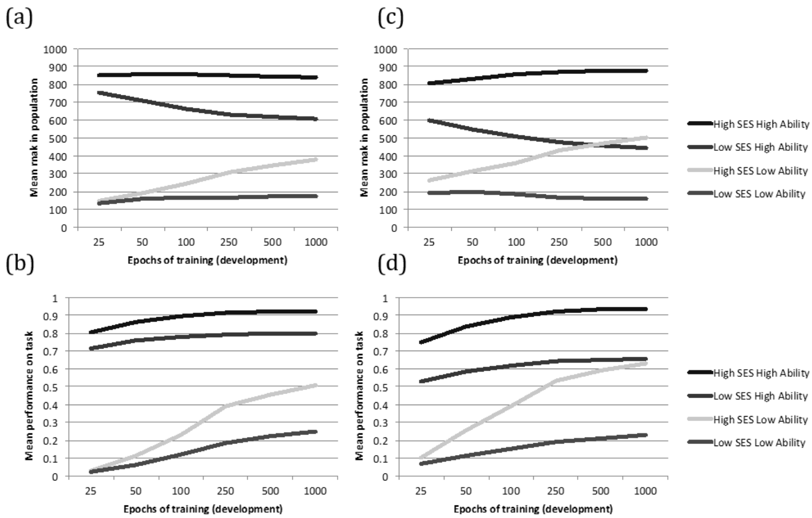


Figure 4 – Simulations of longitudinal change in rank and change in performance across development in the computer model. Rank 1000 = best, rank 1 = worst. SES parameter varies between 1 (highest) and 0 (lowest). (a) Mean change in rank for high and low ability groups defined at time 1 (epoch 25), where high is rank >650 and low is rank <350, split by SES, where high >.5 and low <.5. (b) Equivalent performance on task (proportion correct). (c) Mean change in rank where high ability is time 1 rank >500 and low ability is rank <500, and where high SES >.75 and low SES <.25. (d) Equivalent performance on task for these group criteria.

Was all the rank change due to the environmental manipulation? Table 1 shows the results of this multiple regression, with the environmental parameter marked in bold, and the respective influence of each neurocomputational parameter below. First, it is worth noting that in the simulation, since environmental differences acted throughout development, they influenced measures of ability even at the early stage of development, here explaining 22.7% of the variance at the first time point. Early measurement does not give an unbiased measure of 'genetic' ability free from SES influences. Second, as expected, environmental differences did account for a significant amount of variance in children's change in rank across development, up to 10% at the final time point. But notably, a number of neurocomputational parameters also contributed to change in rank. These included parameters influencing the capacity and plasticity of the mechanism, and consequently the shape of the developmental trajectory.

In other words, the model highlights that children develop at different rates. Some children are late bloomers, others slow later in development. This will cause changes in population rank order that are not solely related to variations in environmental stimulation. It is not necessary, therefore, to conclude from the Feinstein plot that the only cause of changes in children's population rank is due to environmental causes such as SES. In turn, this implies that not all the change in rank would be removed by reducing SES disparities.

Table 1 – Model of prediction of developmental change.

Parameter	Neural network processing role	Predictors of developmental change in Population rank against Time 1				
		Time 2	Time 3	Time 4	Time 5	Time 6
Model fit (R^2)		0.181*	0.312*	0.368*	0.379*	0.384*
SES	**Environment**	**0.158***	**0.274***	**0.332***	**0.337***	**0.333***
Hidden Units	Capacity	-0.069+	-0.089*	-0.079*	-0.07*	-0.053+
Architecture	Capacity	-0.185*	-0.212*	-0.171*	-0.142*	-0.129*
Sparseness	Capacity	0.028	0.037	0.036	0.032	0.036
Pruning Onset	Capacity	0.044	0.074*	0.077*	0.074*	0.067*
Pruning probability	Capacity	0.021	0.017	0.004	-0.002	-0.006
Pruning Threshold	Capacity	0.033	0.013	0.006	0.023	0.025
Learning algorithm	Capacity / plasticity	-0.064+	-0.074*	-0.107*	-0.119*	-0.138*
Learning Rate	Plasticity	-0.148*	-0.159*	-0.177*	-0.186*	-0.199*
Momentum	Plasticity	-0.077*	-0.091*	-0.109*	-0.108*	-0.105*
Weight variance	Plasticity	0.006	0.004	0.033	0.043	0.052+
Unit activation function	Plasticity / signal	-0.107*	-0.147*	-0.178*	-0.184*	-0.188*
Noise	Signal	0.019	0.036	0.069*	0.101*	0.116*
Response threshold	Signal	-0.223*	-0.292*	-0.304*	-0.308*	-0.309*
Weight Decay	Signal	-0.004	-0.015	-0.011	-0.003	-0.003

+ $p < 0.05$ * $p < .01$

Note. Level of environmental stimulation and neurocomputational parameters as predictors of *developmental change* in the model, measured by individual's change in population rank performance across development (scores show standardized beta coefficients from a linear regression model). Neurocomputational parameters are labelled according to their approximate processing role. Both environmental stimulation and network parameters explain variance in rank change (environment is marked by **bold**). The rightmost column indicates predictors of whether an individual's performance (rank) as an adult exceeds the rank of the quality of their environment, as an indicator of *social mobility*. Time 1 = 25 epochs of training, Time 2 = 50, Time 3 = 100, Time 4 = 250, Time 5 = 500, Time 6 = 1000.

Simulation 3: Genetic constraints on social mobility

The model considered SES effects against the background of genetically influenced variations in learning ability. Thus, these simulations were able to capture the high heritability of behavior. For example, heritability of behavior shown in Figure 4(a) at the final measurement point was 51% under an additive model, computed from the twin design. The genetic component also allows the simulation to address data on social mobility. In the model, social mobility is defined as a developmental outcome that is greater or lesser than the SES of the family in which the child is raised (Thomas & Meaburn, in preparation). This can be measured as the difference in population rank order of a family's SES compared to the simulated child's population rank order ability at the end of training. For example, if the SES rank was 500 and the ability rank was 600, this would qualify as upwards social mobility; if the SES rank was 500 and the final ability rank was 400, this would qualify as downwards social mobility. Table 1, rightmost column, shows the results of a multiple linear regression predicting the rank disparity measure of social mobility from each simulated child's parameters. Notably, SES itself predicted a reliable amount of the disparity measure. Much of this relationship was driven by networks that fell below expected levels in high SES environments, less by networks that finished above expected levels in low SES environments. Several of the neurocomputational parameters relating to the network's capacity were reliable predictors of the disparity measure. These indexed whether the network had the capacity to best take advantage of the information that was available in the environment.

To the extent that the capacity of learning mechanisms is genetically influenced, this simulation therefore captured genetic influences on performance and on social mobility. It is the same simulation that captured empirical data on widening IQ gaps from SES across development. The same simulation that captured the restrictive effects of SES on children deemed high-ability early in development. These diverse behavioral effects were captured in a single mechanistic framework.

Simulation 4: SES effects on brain structure

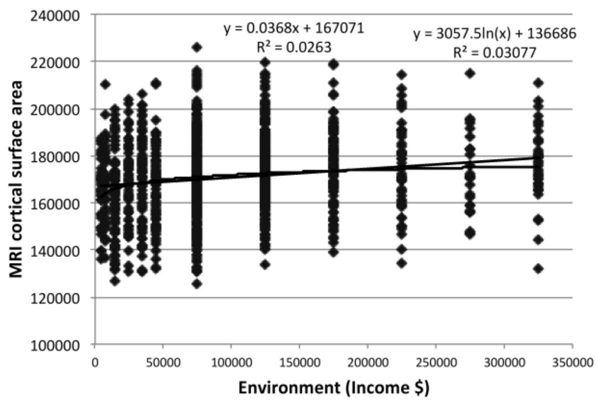
Can the model also capture data on brain structure? The links between the model and brain structure can only be weak, because the model has a very limited degree of biological realism, necessitated by the requirement to make contact with high-level behavior. Moreover, there is still controversy how the physical properties that structural brain imaging measures relate to cognitive function. Despite the fact that cognitive ability shows broadly a monotonically increasing function with age, some of the brain structure measures reduce from middle childhood onwards (grey matter volume, cortical thickness), while others increase (white matter volume, cortical surface area); and the underlying biological mechanisms are still a matter of debate (Natu et al., 2018; Noble et al., 2015).

The model did not simulate the growth of each network, rather capturing variability in the outcome of the growth amongst its parameters in terms of network architecture (pathways linking input and output), number of processing units, and denseness of connectivity. It did, however, simulate a reduction in connectivity from mid-childhood onwards, in terms of a pruning process with variably timed onset that removed unused connections (see Thomas, Knowland & Karmiloff-Smith, 2011). For the artificial neural network, two structural measures offered possible analogs to brain measures: the total *strength* of connections in the network and the total *number* of connections. During training, the total strength increases as those useful in driving behavior are strengthened, while the number of connections reduces as those not useful for driving behaviour are removed. These two network measures provide possible analogs to cortical surface area / white matter density and cortical thickness / grey matter density, respectively, by virtue of their similar developmental trajectories.

Figure 5 takes a mid-point in development for the simulated population considered in the previous sections. Figure 5(a) re-plots data from a sample of over 1000 US children aged 3-20 linking cortical surface area to family income (Noble et al., 2015). A small amount of variance is explained, with a non-linear function that exhibits stronger effects on brain structure at the lowest income levels. Figure 5(b) plots total connection strength for the simulated population against level of stimulation. Again, small amounts of variance are explained, and a non-linear function gives a best fit. Thus, the same simulated population that captures cross-sectional empirical data on SES effects on behavior can also capture cross-sectional patterns observed in brain structure data.

The model offers two benefits at this level. First, it provides a candidate hypothesis about the functional relevance of the brain structure measures – that they represent changes of connectivity arising from experience-dependent developmental change. Second, because the functioning of an artificial neural network is well understood – in terms of activations of networks of integrate-and-fire neurons, and learning algorithms that update connectivity and thresholds – it then demonstrates how indices of network structure only serve as an indirect measure of function, and how function modulates structure as a consequence of (variable) experience.

(a)



(b)

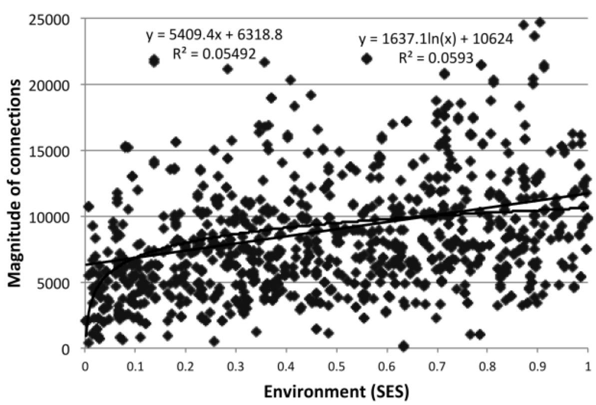


Figure 5 – Empirical data re-plotted from Noble et al. (2015) showing the relationship between annual family income ($) and cortical surface area (mm^2) in a sample of 1099 US children between the age of 3 and 20. (b) Computer simulation data showing the relationship between level of cognitive stimulation in the environment in which children are raised, and the total magnitude of connection strengths in each artificial neural network, assessed at a mid-point in development (500 epochs of training). Both plots show a non-linear (log) relationship between the environmental measure and the structural measure, as well as much unexplained variability (linear and non-linear fits are shown, along with respective R^2 values).

Discussion

A multi-level neurocomputational model was able to capture both behavioral data and brain structure data on the effects of differences in socioeconomic status on development. It did so while also incorporating the contribution of genetic variation to cognitive development, leading to high heritability of behavior; and by assuming that SES operates via differences in levels of cognitive stimulation. Variation between individuals was conceived as the modulation of trajectories of development, driven by species universal mechanisms.

In the simulation data presented, SES was implemented as variations in the level of cognitive stimulation. However, a modeling framework provides the opportunity to implement and compare alternative hypotheses, for example in how well they capture the effect size and shape (linear, log) of SES effects on particular measures of behavior and brain structure. Thomas et al. (in preparation) compared two alternative hypotheses: that SES may instead influence the growth of the networks themselves (per the findings of Betancourt et al., 2016), and therefore processing capacity; or that SES may influence both network growth and cognitive stimulation, in a correlated manner. The computational model therefore provides a foundation to hypothesis test different causal accounts of empirical data.

Thomas et al. (2019) have argued that once a basic developmental model of cognitive variation exists, it provides the basis to explore interventions, for example, by altering the quantity and quality of cognitive stimulation that individuals experience. The next step for the model, then, is to explore whether the gaps between individuals at different SES levels can be closed or eliminated by interventions that equalize environments, for instance by supplementing the stimulation received by children from low-SES families. Thomas and Meaburn (in preparation) carried out these simulations, considering the extent to which opportunities to close gaps depended on the origin of individual differences (e.g., how heritable they were) and whether interventions were modulated by changes in plasticity with age (Thomas & Johnson, 2006). The broad pattern was that equalized and enriched environments improved population means under all conditions; when heritability was higher, improvements were smaller and gaps reduced less; but earlier interventions served to reduce gaps more than late interventions.

The research described here is presented to argue for the utility of neurocomputational modeling as one research tool to further the neuroscience of poverty. One should be cautious, however, to see such models in context. Models do not demonstrate what is actually the case: they demonstrate the sufficiency of particular mechanistic accounts to explain the observed empirical data; and therefore, indirectly, what any given pattern of empirical data must imply about causal mechanisms. By demonstrating the possible causal explanations of data, they do at least encourage the avoidance of misinterpretation of those data. For example, the pattern of widening IQ gaps across SES groups across development might be interpreted to mean that the action of SES differences worsens; the model showed the pattern would emerge even with static causal SES factors. The decline of population rank for early high ability children from low SES backgrounds could be interpreted to mean that population ranks are entirely dependent on environmental factors; the model showed that the empirical data are consistent with a limited role of environment in children's respective abilities. The influential role of SES on cognitive development and educational attainment might be taken as supporting a social causation account of SES differences, and of the primary role of environment in children's outcome. The model displayed realistic SES effects both on behavior and network structure while displaying high heritability of individual differences, even indeed the heritability of differences in social mobility.

Clearly, the model presented here is highly simplified. While it shared some principles of neural processing, it is not a model of brain function. It is essentially a machine-learning mechanism that acquires a small set of input-output mappings, representing at best a single component of a larger system. A more realistic model of SES effects on development would need to depict a goal-oriented, adaptive, autonomous agent, with a repertoire of behaviors that can alter its subjective environment; to include separate cognitive, affective, and reward-based aspects; and provide a pathway for non-cognitive dimensions (diet, chronic stress, fitness) to alter its processing properties. And clearly, there is a great deal more to phenomena such as social mobility (and the societal structures that support or hinder it) than notions of cognitive stimulation and properties of developmental mechanisms.

Nevertheless, the key motivation for constructing a model of the current level of simplicity is to emphasise the importance of deriving causal, mechanistic accounts to explain the large body of correlational evidence that has accumulated on how SES is associated with differences in cognitive, educational, and life outcomes. Computational modeling is but one amongst several neuroscience methods that can shed light on mechanism, methods such as brain imaging, anatomy, animal models, and genetics. Mechanistic insights ultimately provide the basis to derive targeted interventions that can ameliorate the consequences of differences in SES, and especially poverty (Thomas, 2017). The potential of mechanistic insights to inform intervention is the motivating factor behind the involvement of neuroscience in a social issue such as poverty – even if the wider ambition is to alter societal structures that contribute to poverty in the first place.

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11

HOW MIGHT DATA-INFORMED DESIGN HELP REDUCE THE POVERTY ACHIEVEMENT GAP?

J. Derek Lomas

Introduction

Over the past few decades, there has been a substantial drop in global rates of extreme poverty (Pinker, 2018). One big exception, however, is the United States of America, where rates of childhood poverty have substantially increased (Putnam, 2016). While academic achievement is one of the most reliable ways to rise out of poverty, the poverty achievement gap in US education is a barrier that many students do not overcome (Putnam, 2016). While the race achievement gap has narrowed over time, the poverty achievement gap has grown substantially; now, the difference in student performance between rich and poor students is nearly twice the difference between white and black students (Reardon, 2011).

While various approaches have been investigated to reduce the poverty achievement gap, "data-driven decision making" has been found to be particularly efficacious (Fryer, 2017) and cost effective (Yeh, 2010). This approach uses formative assessments (e.g., quizzes and topic tests) to systematically measure student needs so that incremental support and solutions can be provided in response. While mostly used in the context of a single school or district, this chapter will focus on the potential for data-driven design to incrementally drive improvement in nationwide K12 digital curriculum systems.

The promise of digital curriculum systems -- i.e., those that accompany traditional textbooks -- is that they can reach millions of disadvantaged children via public schooling (Fletcher et al, 2012). System enhancements can therefore be scaled rapidly to millions. While the effect of any single system enhancement will likely be small, a continuous cycle of need-driven improvements can make a meaningful -- and measurable -- impact on the poverty achievement gap.

Digital curriculum systems are not entirely digital. These systems often include physical textbooks, digital and non-digital formative assessments (e.g., topic quizzes), instructional resources (e.g., online videos), teaching support (e.g., teacher manuals) and teacher training (i.e., professional development). These curricular systems are complex socio-technical systems that scaffold the interaction of students, teachers, and administrators while operating across textbooks, paper, laptops, mobile phones, and even human dialogue. How can digital curriculum systems use data to reduce the achievement gap? At the core, these systems must be capable of measuring the needs of struggling students so that different stakeholders can do something about it. Existing systems can improve faster when they support two key functions: the assessment of needs and the adaptation of the system in response to those needs.

This chapter is structured in the following way. I begin with a review of childhood poverty in the USA. Then, I describe data-driven design methods and why they are not more widely used to improve digital curricular systems. The middle of the paper offers two set of data-based evidence. In the first, I examine the effects of poverty on student performance in a digital curriculum system and show the feasibility of prioritizing topic-level system improvements. In the second, I share a series of recent online controlled product experiments to demonstrate how a data-driven design approach can contribute to scientific discovery and outcome optimization. Following the presentation of evidence, I discuss opportunities for the evolution of artificial intelligence (AI) in support of human development. I note that both AI and data-driven decision making require valid and reliable measures of the desired outcomes — and, therefore, indicates that there is a critical need for improvements in the school-based assessment of factors of both childhood poverty and childhood well-being. Prior to this conclusion, I share a brief cautionary tale of what can go wrong with a large-scale education system transformation. In the conclusion, I encourage business owners, politicians, scientists, and designers to collaborate and work together on this problem: to design infrastructure for digital education that can measure the needs of struggling students and support them, intelligently, in order to more broadly cultivate human potential.

Childhood poverty in the USA

The United States of America is a rich country. And yet, among the world's richest 35 countries, the United States has the second highest rate of childhood poverty, topped only by Romania (Adamson, 2012). In the 1970s, rates of childhood and elderly poverty were both 15%. Since then, elderly poverty has nearly dropped by half, to 8.8%, and childhood poverty has increased to 19.7% (DeNavas-Walt and Proctor, 2015). Currently, 24% of K-12 schools are considered "high-poverty" (defined as having >75% of students who qualify for free/reduced price lunch; NCES, 2018). Ironically, high rates of poverty run counter to deeply held political beliefs: over 90% of Americans agree with the statement "Everyone in America should have equal opportunity to get ahead" (Putnam, 2016).

Childhood poverty is a complex problem that can inhibit learning and development through various mechanisms, from the biological to the sociological (Lipina, 2016). Many fields study the effects of poverty on development, including economics, sociology, anthropology, psychology, neuroscience, educational research, and others. This paper uses the word "poverty" as shorthand to refer to a range of different measures of poverty and lower socioeconomic status (lower-SES). According to a recent count (Spicker et al., 2007), there are 194 different operational definitions of poverty. Income is, of course, central to poverty — but poverty itself is *a multidimensional construct based on deficits in well-being* in multiple areas like health, education, social support, and social status (Lipina, 2016). The effects of poverty and lower-SES on student outcomes are statistical correlations; individuals can overcome their circumstances. Still, childhood poverty is a significant barrier to individual success and well-being and can cause long-lasting negative effects.

The moral and economic potential in reducing poverty

Childhood poverty is a moral issue. The choices made by children do not cause their own poverty - yet, the circumstances of childhood poverty can limit individual potential. As adults, children born into poverty often remain in poverty because of the lack of educational and career attainment: this is "the poverty trap" (Banerjee et al, 2011).

The economic cost of childhood poverty has been estimated at $500 billion USD per year in the USA alone (Holzer et al, 2008). Children coming from a high-poverty background are more likely to have reduced language, reading, and executive functioning skills (Hackman and Farah, 2009), which can make it substantially harder to successfully attain higher education and higher-salary jobs. In fact, individuals from high poverty backgrounds make only half as much money as their peers from higher-income backgrounds (Coley & Baker, 2013). While educating children from high-poverty backgrounds is more costly than educated well-off children (Duncombe & Yinger, 2005), the return on investment is greater: economies see $2.5 to $7 in return for every dollar spent on targeted education (Peters, et al., 2016).

The effects of poverty on learning

Why does poverty negatively impact learning outcomes? Foremost, deficits in certain human needs are theorized to reduce cognitive performance, hindering student growth potential. For instance, poor nutrition, sleep, obesity, and increased numbers of adverse childhood events (ACEs, e.g., abuse, neglect, divorce) are associated with reduced self-control and working memory (Lipina and Evers, 2017). For an obvious example, if a child has insufficient sleep, it is harder to focus, making it harder to learn. A downward spiral results when low school achievement results in expectations of failure, lowering scholastic motivation and further impairing future learning.

There is a financial incentive for education companies to attend to the needs of high-poverty schools. High-poverty schools in the USA can often qualify for federal grants, meaning that higher-poverty schools often have access to funding for educational supports. That said, only 0.008% of national education spending ($800 billion USD) goes towards digital education content (Council of Economic Advisors, 2011). While this limits participation in the current market, the upside is that there is a lot of room for the industry to grow.

Given the moral and economic imperative to address childhood poverty, the next section of this chapter more closely examines how data-driven design techniques in K12 learning software could provide targeted impact. While there are many routes to support positive social change, improvements in digital systems appears to be a "low-hanging fruit." We hypothesize that digital improvements to learning software are a scalable and cost-effective mechanism for incrementally increasing student outcomes in high-poverty schools across America.

Data-driven improvement in digital education

As designers, we ask: how might we design computational systems to support the developmental needs of underprivileged children? Scientists have identified and evaluated various educational interventions that can help support struggling students from high-poverty backgrounds in developed (Fryer, 2016; Yeh, 2010) and developing countries (Ribeiro et al, 2016; Banerjee et al, 2012, McEwan, 2015). Some of these interventions require a great deal of personal involvement and some are relatively easy to scale. Some interventions are slight modifications of existing systems, while others represent dramatically different ways of managing schools. A subset of these interventions might be delivered digitally on large-scale learning systems.

Why is data so important, anyway? From first principles of information theory and cybernetics, all intelligent systems use data as feedback to guide action (Weiner, 1949). A simple learning loop, like a thermostat, involves a simple comparison system where a goal is defined in terms of a particular outcome measure, like the temperature. At a simple level, measurements provide data to inform systems whether goals have been achieved. A thermostat, however, has only one measure (temperature) and one action (turning a heater on or off). In more complex systems, the potential space for measurement and action are far more complicated — but the basic principles of feedback still apply. This is the simple story of a feedback loop (Argyris & Schon, 1978).

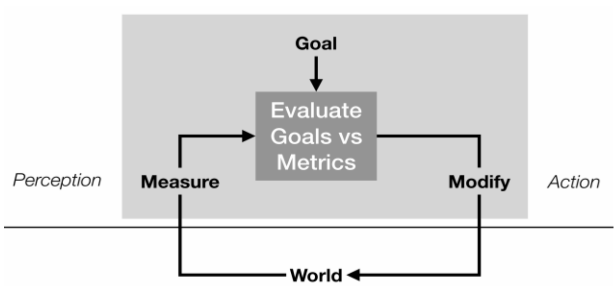


Figure 1 - A simple cybernetic loop. For instance, a thermostat continually measures the temperature in the world, compares the measure against a goal and then turns on the heat if necessary. This data-informed feedback cycle is pervasive in human society.

This data-driven improvement approach is not uncommon in education. Mastery learning provides a particularly good example. In a mastery learning context, teachers will provide instruction on a particular topic with the goal of student mastery. They will then assess students for mastery. If the assessment indicates that students have mastered the topic, then the goal has been fulfilled and the teacher goes on to the next topic. If the assessment indicates that students have not mastered the topic, then the teacher provides revised instruction and assessment, until all students reach mastery.

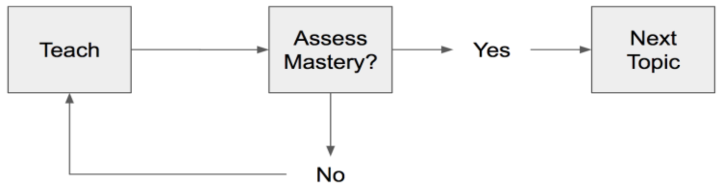


Figure 2 - Flow diagram of Mastery Learning (Bloom, 1968).

How do we envision applying this simple (but actually, very complex) process to large-scale digital curricula systems? In an idealized system, valid data from the usage of a digital curricula system is collected. These data are made accessible within a data report that is analyzed by various stakeholders. For instance, product teams might reflect upon metrics for areas of need within the digital curriculum, such as student failure or drop out. If a particular component of the learning system is failed at a higher than expected rate (e.g., fraction addition), then teams can reflect and seek insight on the specific reasons why. These reasons can then be used to prompt a design modification. For instance, there might be a usability issue that prevents the use of existing instructional resources. Or, perhaps teachers need a broader range of instructional resources, or better diagnostic assessments. These design optimizations can then be deployed to users and the process can start anew.

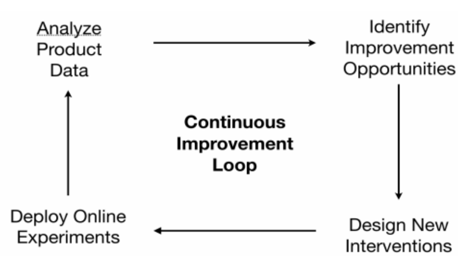


Figure 3 - Starting at the top left, digital product data can be used to identify areas of need. E.g., if high poverty students disproportionately fail at a particular topic, this represents a product improvement

opportunity. Then, new interventions can be designed for this area of need. The efficacy of those interventions can then be empirically tested using online product experiments, which produce data that can feedback into this continuous improvement loop.

Data-driven design (or more precisely, data-informed design) begins with a definition of goals (or needs). Second, these goals are transformed into outcome measures that can suitably indicate when those goals have been achieved (or needs satisfied). Even these two basic ideas — setting the "right" goals and determining the "right" measures of the goals — carry an incredible amount of complexity and potential for error.

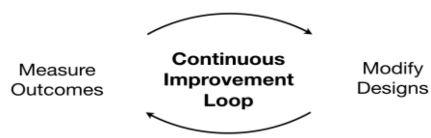


Figure 4 - A simplification of the continuous improvement loop consists of an iterative cycle of measuring outcomes, then modifying systems, measuring the outcome, etc. Another way to describe this is "assessing needs" and then "doing something about it" in a continuous cycle.

Data-driven design means the implementation of processes that can regularly carry out these measures and take actions to modify the current system when goals aren't met. Speaking plainly, systems need to be able to measure needs and then to do something about them. Deciding which actions to take, of course, is another major source of complexity. Then, when the designs have been modified, again outcomes can be assessed to see if needs have been satisfied. The process can repeat until needs are satisfied.

Data-Driven Improvement is relatively rare in educational software. Not so in other commercial industries (LaValle, 2011), where it goes by various names, such as Continuous Quality

Improvement (Clark et al, 2013), Lean, or Data-Driven Design (DDD, or D3: Likkanen, 2017; Kim et al, 2017). In classroom education, there is a substantial literature on data-driven improvement, where it is alternatively called Data-Based Decision Making (DBDM; Schildkamp et al, 2012) or Data-Driven Decision Making (DDDM). The K12 educational literature tends to focus on data practices by teachers and school administrators; in higher education, the recent literature has centered on Massive Open Online Courses (MOOCs) (Kizilcec, 2015).

In a school administration setting, data-driven decision making involves gathering data (typically test scores), analyzing data to identify problems (and their root causes), and then selecting actions that can address those problems (Slavin et al, 2013). Van Geel and colleagues (2016) describes the administrative process in terms of data analysis, SMART goal setting (Specific, Measurable, Attainable, Realistic, Timely), strategy development for goal accomplishment, and then execution. Several controlled experiments have demonstrated positive benefits of introducing data-driven decision making to schools and districts, such as Slavin et al (2013), Fryer (2017), and van Geel et al (2016). Data-driven decision making has been found to be particularly effective in high-poverty schools (van Geel et al, 2016) — this is notable, considering how few interventions have been found to be effective in addressing the achievement gap (Fryer, 2017). However, there are many barriers to applying data-driven decision-making in schools: Schildkamp et al (2014) describe a lack of quality data, a lack of skills in using data and a lack of stakeholder collaboration in using data. There can also be significant risks from unintended consequences: when the data are used for accountability purposes, there can be perverse incentives that cause schools to encourage low-performing students to drop out or to cheat (Schildkamp et al, 2012).

Barriers to data-driven continuous improvement in digital curricula system

Responsiveness to data is viewed as a central component for the future of digital education, particularly in support of adaptive learning systems (West, 2012). Ironically, there has been virtually no scientific engagement with the data-driven improvement of instructional content within K12 digital curriculum systems.

A review of the Learning Analytics field (Chatti et al, 2012), for instance, categorized different applications of digital learner data: 1. monitoring and analysis 2. prediction and interventions 3. assessment and feedback 4. intelligent tutoring and adaptation 5. personalization / recommendation 6. individual reflection. None directly dealt with improvements to curriculum itself. In studies of data-driven decision making in schools, data are used to choose entire curriculum programs but not specific curriculum elements or lessons. That is, measures of school-level needs, like reading skills (as in Slavin, et al, 2013), were used to motivate the adoption of new reading programs; however, assessments of particular sub-skills were not used to adopt specific instructional materials (i.e., lessons) for those sub-skills. The use of curriculum analytics to inform specific curriculum improvements is presently a missed opportunity.

Barriers to data-driven design

What are the barriers that prevent data-driven curriculum improvement from being applied at large curriculum organizations? Many of the companies offering digital learning software are textbook companies. While textbook companies are familiar with making new editions of a textbook, they are not used to continuously improving their software products over time (Fletcher et al, 2012). Because they typically sell multi-year contracts to state or local governments, there are sometimes arcane legal provisions that forbid or inhibit any changes to existing products, even improvements.

Curriculum companies are complex socio-technical systems that have many, many stakeholders: product owners, executives, instructional designers, software engineers, sales staff, marketing, teacher users, student users, administrative users, etc. Because there are so many stakeholders involved with large legacy software platforms, it can be very difficult, expensive, and risky to make changes.

Many K12 digital curricula companies collect an enormous amount of data but struggle to make use of it. This is due both to a lack of data science capacity and to public perception risks of using educational product data. For instance, a recent attempt by one large educational company to run controlled product experiments resulted in a several point drop in their stock value[15]. Their goal was to test different motivational feedback messages but this was described in the press as "psychosocial manipulation."

Perhaps the most important barrier to continuous improvement is financial incentive: while companies like Facebook have revenue based on usage, education companies do not. Nor are educational companies paid based on outcomes. Most education companies won't receive more money if their software is improved; thus, improvement is a cost without a reward. As a result, these companies do not have a direct financial incentive to improve their digital products to improve student performance or outcomes. Nevertheless, in our experience, there are often many employees in these companies that care very much about improving student outcomes. Despite the barriers mentioned, times are changing quickly. Increasingly, school districts and

[15]https://seekingalpha.com/news/3348015-pearson-slips-report-tracked-students-social-experiment

governments are expecting more concrete results for the money invested and have begun to make use of overall usage data in their evaluations, i.e., if teachers and students rarely use the software, the contract is not renewed. Another potential nudge for data-driven improvement (specifically, for running product experiments) comes from the new USA ESSA federal guidelines[16] that encourage schools to purchase "evidence-based" products, i.e., products that can show proof of efficacy using controlled experiments. If product experiments are cheaper to run than traditional classroom experiments, this could change behaviors.

Empirical findings

The next section examines data from a large online curriculum system in relationship to the issue of childhood poverty in the USA. This study describes how online performance data can be used to prioritize product improvements to support the specific needs of students attending high-poverty schools (or any other sub-population, for that matter). I first evaluate the effects of various demographic factors on student performance, highlighting the dominant role of poverty. Then, I examine correlations between poverty and performance on specific math topics. Finally, I correlate performance on specific math topics to summative test scores; this provides a plausible route to prioritizing product improvements based on the relative importance of learning the topic. In theory, data like these could be used to drive system-wide improvements in any organization that has overcome internal barriers to continuous improvement.

[16] https://www2.ed.gov/policy/elsec/leg/essa/guidanc euseseinvestment.pdf

Identifying needs of high-poverty schools using large-scale learning systems
This section presents a combination of data from an online learning system and online demographic databases in the USA. This analysis does not involve data about individual student poverty levels, but rather uses USA federal government statistics about school poverty to investigate correlations with average school performance in a popular digital math program. Thus, while we cannot report on the relationship between individual family income levels and student performance, we can report on the effect of school poverty on average student performance therein.

The US federal government maintains records on the poverty levels of every school in the US. Two key statistics are the average income level in the school neighborhood and "School Lunch Percentage", which tracks the percent of students in the school that qualify for free/reduced price lunch due to low income. While eligibility for this program correlates with poverty, it is not a direct measure — it is just the most widely available correlating statistic[17]. Schools with over 75% of students qualifying for a free or reduced priced school lunch are considered high-poverty schools.

To investigate the needs of high poverty schools, we joined the government data with a database of student usage and performance within a widely-used digital curriculum system. We used a subset of data from 529 schools using a 5th grade math program. When we plot average student percentile performance against the poverty levels of the school, we find that there is a strong linear correlation between rates of school poverty and digital math performance. While there are high-poverty schools that perform very well and low-poverty schools that struggle

17 https://nces.ed.gov/blogs/nces/post/free-or-reduced-price-lunch-a-proxy-for-poverty

mightily, poverty appears to account for a performance drop of over 15 percentile points in 5th grade math.

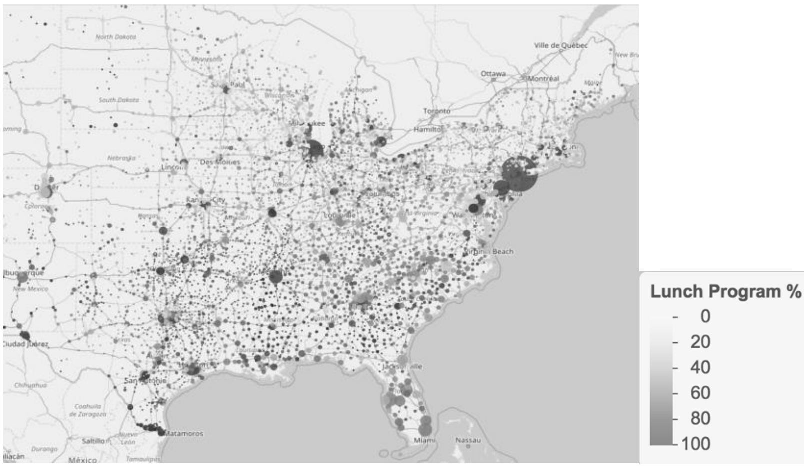
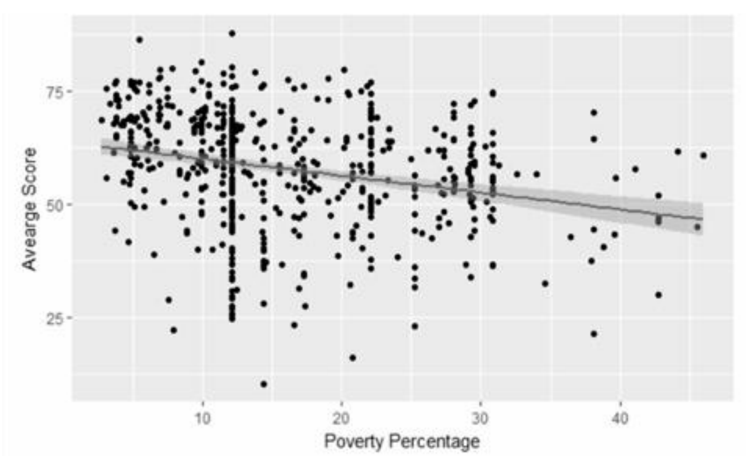


Figure 5 - Regional poverty map of schools in the central and eastern United States. Each point represents a school, and the size of each point corresponds to the size of the school. Darker points represent higher levels of school poverty. This figure helps illustrate that more than 25% of US schools are considered "high poverty" (NCES, 2018).



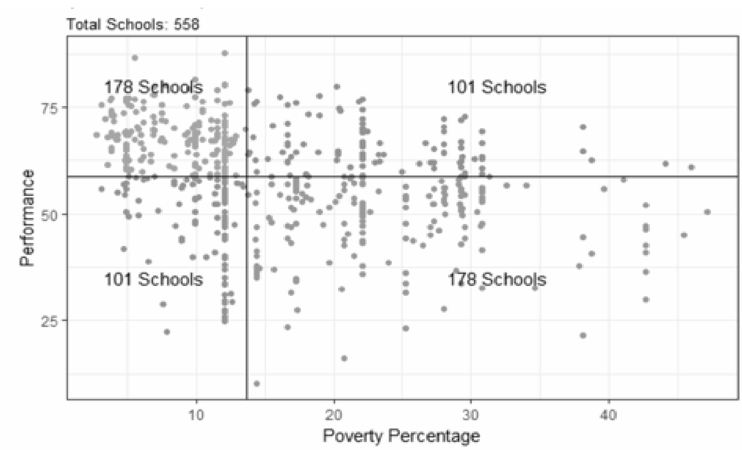


Figure 6 - The poverty achievement gap can be visualized within individual digital learning products. The Y-axis shows the average percentile score on math formative assessments for over 55,000 students in 529 schools. The X-axis shows the percent of students in the school receiving free or reduced school lunch, which is a common measure of poverty. This illustrates the nearly 30 percentile points that separate the highest poverty schools from the lowest poverty schools – and also illustrates interesting outliers (e.g., top right quadrant) that could inform improvement for the schools struggling the most (bottom right quadrant).

To better consider the multifaceted nature of this relationship, consider Table 1 below. The in-school usage of the digital curriculum system had a small correlation (-0.12) with poverty levels, indicating that the usage of the digital product was nearly equivalent between high and low poverty schools. This is promising, as home-based learning programs (like Khan Academy) are often used at a far greater rate by middle and upper-class families (DiSalvo et al., 2016).

Table 1 - Demographic and school input factors from the government data along with digital metrics from the curriculum system.

Factor Type	Independent variables	Correl. with Poverty(% F/R Lunch)	Correl. with Formative Assess. percentile	Effect Size on Formative Assess. (Cohen's *d*)	Relative importance (variance explained)
Demographic	% ELL	0.38	-0.16	-0.34	1.12%
Demographic	%Poverty(%F/R Lunch)	1.00	-0.62	-1.36	24.49%
Demographic	Local Income	-0.77	0.53	1.04	41.74%
Digital Metric	After School Usage	-0.24	0.32	0.59	11.17%
Digital Metric	In-School Usage	-0.12	0.21	0.38	4.09%
Digital Metric	# Assessments	-0.20	0.30	0.52	9.19%
School Inputs	Hardware Spend per	0.36	-0.39	-0.72	19.49%
School Inputs	Instructional Spend per	-0.19	0.05	0.09	1.72%
School Inputs	Software Spend Per	0.13	-0.24	-0.37	8.11%
School Inputs	Total Spend Per	-0.18	0.08	0.19	3.59%
School Inputs	Student Computer Ratio	-0.02	0.00	-0.07	0.05%
School Inputs	Student Teacher Ratio	0.23	-0.08	-0.24	0.63%
School Inputs	Total Students	-0.01	0.03	0.02	0.21%

Note. In the first column, we show correlations with poverty (the percent of students receiving free/reduced price lunch). In the second column, we show correlations with average performance on formative assessments (topic quizzes) that are used within the program (formative assessment percentile). We then calculated the effect size (in standard deviations, Cohen's d) of the shift between high and low poverty schools. Finally, we built a regression model of all factors to predict the formative assessment percentile) and conducted a variance decomposition procedure. This allows us to report the variance explained by each factor, as a matter of "relative importance" of the feature to average performance.

The biggest effect on performance came from local income and the percentage of students enrolled in school lunch programs. Interestingly, spending per student does not correlate with performance; this appears to be the case because higher-poverty schools receive additional grants. The other correlations reported here are presented as discussion points towards a more complete analysis (which we feel would be necessary to validate decisions made based on these data).

Transforming test data into areas of need

The previous section showed that school poverty highly correlates with student performance in a digital math curriculum system. However, none of these correlations really suggests a particular course of action. For instance, while hardware spending negatively correlates with digital performance, this is likely a result of increased grant funding in high-poverty schools. To be able to suggest actions for improvement, one need to highlight components of the digital math program that, if improved, are likely to yield the most improvement in high-poverty schools. Therefore, the next section aims to show how to use digital performance data to provide actionable recommendations for improving outcomes in high-poverty schools.

The goal, simply, is to improve performance in high poverty schools. The quantitative measure of goal achievement used here is student success on end-of-year tests. The model of impact is improving the quality of digital curriculum resources available to teachers and students. As there are limited resources for improving these instructional resources, the objective here is to prioritize specific curriculum elements for subsequent improvement.

To prioritize the resource investments to support the needs of high-poverty schools, I first identify the topics that are most challenging in high-poverty schools (i.e., topics with performance that correlates most with school poverty). Those are the elements of the current curriculum that appear to be insufficient for topic-level success in high-poverty schools. To further prioritize improvement, in the model I want to take into account the fact that not all math topics are equally important. To obtain a rough measure of topic importance, I identify the topics that are most correlated with poor performance on end-of-year summative tests. In the absence of other information, it can be reasonably assumed that it is most useful to improve student performance on topics with the most correlation with end-of-year tests. These two steps, correlations of topics with poverty and correlations of topics with summative performance, can jointly indicate the biggest areas of need (the most important topics that cause the most failure in high poverty schools). I believe this simple analysis can help prioritize resource investments towards topics where they are expected to have the biggest impact on the poverty achievement gap.

Specifically, I first calculated individual student percentile performance on over 100 different topical quizzes, each of which were used by at least 100 schools in our sample. Then, I averaged the student percentile on these topics to provide a school-level topic score. Then, I examined the correlation between school percentile performance on these topics with end-of-year summative test performance and poverty levels in the school.

The results showed that quizzes were an average of 14 percentile points lower in high poverty schools. However, among these quizzes, there were certain topics that were particularly challenging for students in high-poverty schools. For instance, I compared performance in "estimating sums and differences with fractions". Of the 4580 submits of a quiz in 76 low-poverty schools, average percentile performance was 73%. Of the 2432 submits in 46 high poverty schools, the average percentile score in high-poverty schools was 54%. This is a difference of nearly 20 percentile points.

The below table shows the skills and standards that are most highly correlated with student success on end-of-year tests. That is, low performance on formative assessment quizzes on these topics is most associated with low end-of-year test performance.

Table 2 - Topics or skills that most correlate with end-of-year test performance.

Skills	# Students	# Schools	Correl. with % Poverty	Correl. with End of Year Test
Rounding Decimals	9033	279	-0.62	0.54
Estimating Sums and Differences of Fractions	7192	235	-0.51	0.53
Estimating Sums and Differences of Mixed Numbers	4825	176	-0.58	0.52
Decimal Place Value	8439	279	-0.57	0.49
Solving Problems Using Division	3492	147	-0.49	0.48

Table 3 - Common core state standards that correlate most with end-of-year test performance.

Standard	# Students	# Schools	Correlation with % Poverty	Correlation with End of Year Test
5.NBT.A.4	12677	355	-0.63	0.53
5.NBT.A.3	11932	339	-0.54	0.48
5.MD.C.3	7360	219	-0.44	0.47
5.NF.B.7a	9410	253	-0.45	0.45

In this analysis, I assume that the topics that correlate with both poverty and end-of-year success are likely to have the "biggest bang for the buck" if those topics are targets for improved remedial instruction design. This analysis identified a cluster of problem topics around fraction and decimal skills that were highly correlated with end of year tests and were particularly problematic in high poverty schools. This suggests that investing resources in improving student performance on these topics would lead to improved test performance for all students, but particularly for students in high-poverty schools.

While all of this work is purely correlational, digital curriculum systems permit controlled experiments that could evaluate the causal benefits of any such improvement. For instance, if new resources were developed, they could be experimentally assigned to a small subset of students, classes, or schools. If the experiment reveals improvements in student performance, then further modeling could look for generalized benefits to overall math performance. When resources are found to be effective, they could be rolled-out to all students.

Product design experiments and data-driven design

This section examines a particularly powerful tool in data-driven improvement: controlled product experiments, also known as A/B tests. With this tool in place, digital learning systems have the potential to measure what is working - that is, the specific effects of particular interventions on student outcomes.

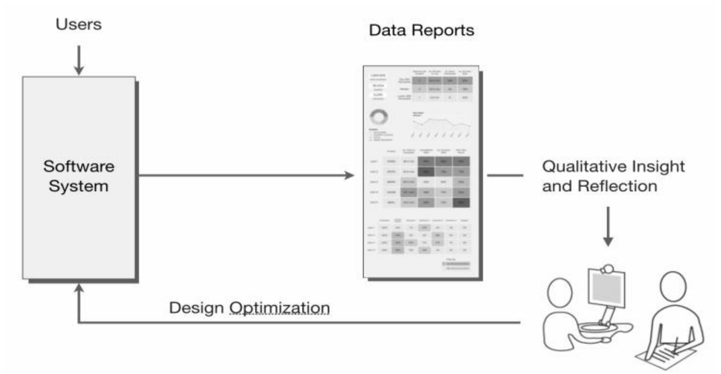


Figure 7 - A data-informed design feedback loop involves qualitative insight and reflection by groups of people. Considerable work is required to make software system data accessible and actionable to product teams - and considerable work is required to translate these data into useful actions for design optimization.

Controlled experiments are one of the most important attributes of large-scale learning systems because they can precisely measure the effects of interventions on student outcomes. Large-scale learning systems therefore have the potential to use experiments to measurably optimize student learning outcomes.

We've all encountered A/B tests on the internet, whether we know it or not. Sites like Google, Amazon, Netflix, Facebook, and many others use "A/B testing" to identify best performing designs. For instance, a small business might design two different landing pages and then randomly assign each visitor to landing page A or landing page B; then, certain outcome measures can be examined: e.g., did people purchase more on the website with version A or B? These controlled product experiments enable empirical evidence to be collected about the efficacy of different designs.

Experiments are widely used in industrial software to increase revenues. Commercial design optimization using scientific experiments can drive design choices based on empirical evidence for efficacy. Troublingly, society disproportionately applies these powerful technologies to the optimization of advertising and rarely uses them for the optimization of education and learning.

Beyond design optimization, online experiments are also capable of testing generalizable scientific theory, as illustrated below. This figure shows how online learning systems are typically designed with reference to certain learning science theories. When a learning system achieves sufficient scale, it becomes possible to run controlled product experiments. These experiments can be used to select among design variations, so that the results can be used to improve outcomes. But beyond that, these experiments can also provide evidence that tests general theories in learning science. For instance, in a later section, we will examine how online experiments in a learning game were used to test Mihalyi Cziksentmihaliy's Flow Theory — and how this theory testing led to optimized student outcomes.

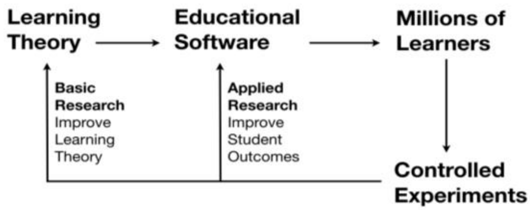


Figure 8 - How can A/B testing and controlled experiments in digital learning products contribute to social impact? The above flow chart shows how learning science and theory is used to design educational software. When this software achieves scale, controlled experiments (e.g., A/B tests) can be used to directly optimize system performance and improve student outcomes. This applied research might focus on how to improve student engagement and increase scores. However, experiments can also be conducted that evaluate theoretical hypotheses and therefore contribute to basic learning science. Scientific findings can then generally contribute to the theory used to inform subsequent educational software designs. Further extensions of this work can be found at upgrade-platform.org, which supports UpGrade, an open-source platform for A/B testing in educational software (Ritter et al, 2020).

Experimentation in learning systems

Controlled experiments presently play an important part of education research, both for validating the efficacy of different curricula and for developing a body of scientific knowledge in education (National Research Council, 2002). These experiments can guide investments in education, both in developed (Fryer, 2017) and developing countries (Banerjee et al, 2011; McEwan, 2015). In Fryer's review of work in developed countries, for instance, early childhood interventions, high-dosage adolescent tutoring, managed professional development, summer reading programs, and data-driven practices were all found to consistently, significantly, and meaningfully improve outcomes. These experiments are typically very costly and difficult to organize; but, because they can guide the provision of large sums of government money, they are viewed as having a high return on investment.

Interestingly, controlled product experiments are less costly to implement (simply changing software configurations), more ecologically valid (occurring within an existing system of practice and without experimenter involvement), and can more rapidly disseminate efficacious results (by increasing the percentage of users that receive the experimental condition).

Online courseware (i.e., MOOCs and intelligent tutors) has been the basis for a number of online experiments in education (Reich, 2015) that contribute to product improvement and scientific progress (Koedinger et al, 2013). However, when it comes to online K12 curriculum, there are few online learning systems that regularly use controlled product experiments for optimizing outcomes. One that we are aware of, Scientific Learning's "Fast ForWord K-12" software (Merzenich et al, 1996), has recently integrated an open-source system (https://facebook.github.io/planout/) for managing large-scale controlled product experiments. The product platform was designed to use controlled experiments (or potentially, AI-based policies) to empirically evaluate novel neuroscience-based digital interventions using embedded assessments.

There are other benefits that stem from controlled software experiments. Fabien et al (2017) reviewed over 300 product experiments at Microsoft and identified 10 benefits of controlled product experiments, such as continuous product improvement, quality assurance and deployment benefits, value quantification, and enhanced team coordination around digital metrics. The field of digital education has even more to gain from online product experiments. Product experiments can help test educational theories, generate evidence for the efficacy of particular components (including the benefits of personalization approaches, as Williams et al, 2014), and support assessment item piloting for psychometric validation and test construction.

AI in Education

Many current models for AI in education are student-facing; for instance, intelligent tutoring systems that mediate the experience between a student and their computer. In my group's engagements with large online curricula systems, we feel it is important to shift to more collaborative teacher-facing models of AI. My research group sees potential in aggregating the intelligent decisions made by thousands of teachers into system intelligence (Patel et al, 2017). For instance, we have been exploring how to learn from teachers who assign interventions to students in response to student performance on a test (Patel, 2018). Certain teachers do this with a much greater frequency because it is difficult and requires a broad range of knowledge over the content domain and the digital curriculum. Therefore, we aim to aggregate the assignments made by individual teachers and make these available to other teachers as recommendations. In this manner, AI recommendations can collaboratively support the work of teachers in the classroom in what can be called "Human Technology Teamwork" (Norman, 2017).

This approach is defined in the following figure, which describes how data from 1000s of classes and teachers can be used to provide adaptive recommendations to teachers. This approach uses a reinforcement learning model, where the collected student assessments serve as the observation space, the potential set of assignable digital resources serve as the action space, and the usage of different recommendations serves as a reward. Ideally, the rewards would be based on the measured satisfaction of student needs.

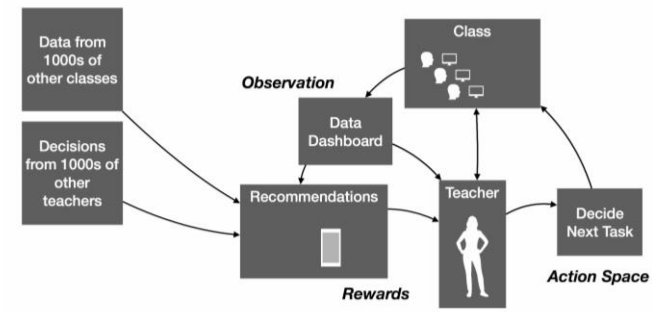


Figure 9 - Reinforcement learning involves creating an observation space (e.g., data about student performance), an action space (e.g., decisions about what tasks or assessments are assigned to students), and a reward system for improving the efficacy of recommendations. In this diagram, data from decisions made by other teachers can inform adaptive teacher-facing recommendations for class actions.

Discussion

Data-driven improvement and childhood poverty

How can large-scale digital curricula systems best support the needs of struggling students and produce positive social impact? Simply put, these systems should measure student needs and then take action to address them. The following sections provides recommendations about how to best design "system intelligence" into educational systems so that we can optimize outcomes in high-poverty areas — by understanding and supporting their needs.

As a first principle, digital learning systems should be able to collect valid digital data about student needs. These data should be made accessible and interpretable at various levels, e.g., teachers, parents, school systems, product owners, etc. This allows for bottom-up innovation, so that insights from successful learning and adaptation at the level of classrooms and schools can be propagated across the system.

From a design perspective, learning systems should endeavor to make remedial instructional resources available to teachers in a just-in-time fashion, in response to the assessment of needs. This makes the data about needs directly actionable. This can be achieved by providing recommended resources within data dashboards used by teachers or school leaders. Further, there may be a need for designing new resources to respond to different common needs, including student and teacher-facing resources for instruction and assessment. Ideally, new instructional resources can be deployed via product experiments to a subset of users in order to test their utility prior to disseminating to all teachers. This may require the development of improved social processes and technical platforms for running controlled product experiments. To broadly realize the objective of building intelligent learning systems to support the needs of high-poverty schools, it is recommended to begin a design-oriented dialogue between learning scientists, neuroscientists, policymakers, digital learning product owners, and software users/teachers.

Most critically, there is a need for consensus on *which* specific needs *should* be assessed, with respect to high-poverty schools. We don't just want to satisfy immediate needs, but support long-term individual and collective growth and well-being. Determining these priorities is partially a question of data (e.g., what near-term needs best correlate with long-term objectives?) and partially a question of values (e.g., what long-term objectives do we actually care about?).

Currently, schools assess student performance using a variety of academic tests and behavioral metrics (e.g., attendance, how often they get in trouble, etc.). While teachers may be aware of issues like hunger or health concerns, teachers don't consistently evaluate these or other dimensions of wellness that affect academic performance. It is also rare for schools to measure other factors, such as executive function skills (e.g., working memory, inhibition control and flexibility) that can mediate the relationship between poverty and academic achievement. To promote equity in education, it is necessary to adapt to the different needs of different students; therefore, this also requires engaging in systematic efforts to measure student needs. We should be attentive to near-term and long-term goals by recognizing that our near-term metrics may not always capture our long-term values.

Assessing factors of well-being

Various deficits in personal well-being may create measurable barriers to cognitive performance and academic achievement: it is much harder to perform (e.g., use executive functions) when one is hungry, sick, tired, stressed, or distracted by negative events. Childhood well-being, considered broadly, is an important mediator of student performance.

What is the relationship between poverty and well-being? Conceptually, poverty can be defined as deficits in needs that are essential to well-being; whether food, shelter, medicine, social support, individual purpose, etc., poverty can be defined in terms of deficits in factors of well-being. Factors of poverty and factors of well-being are somewhat inverse concepts that can be placed on the same scale, like sickness and health.

From this perspective, one can consider the evidence that working memory is inversely related to childhood poverty, with the presence of chronic stress as a mediating factor (Evans and Schamberg, 2009). From a design perspective, it might be predicted that interventions that improve childhood well-being could themselves reduce chronic stress and (partially) mitigate the negative effects of poverty on working memory and academic achievement. Each of these factors — working memory, chronic stress, and well-being — are appropriate measurement targets to support a data-driven continuous improvement approach in online learning systems, yet none are measured today in typical school systems.

It is intuitive that deficits in well-being create barriers to development and academic achievement. Let me give credit to my own daughter's Montessori teacher, who said, "You can't learn well if you don't feel well." But, the scientific process expects intuitions to be validated. The challenge is that, currently, it is difficult to measure well-being in children. If deficits in well-being mediate scholastic performance, it is critical to develop and validate different measurements of well-being for accessible use in caregiving settings. And, while there do exist a number of instruments for measuring adult or adolescent well-being through self-report (Rose et al, 2017), these may not be appropriate for use with young children.

One area for future research is the development of accessible and easy-to-use observational assessments for teachers to rate their perceptions of various factors of well-being. With improved measurement, it would be possible to 1) identify general areas of need within a school, 2) to identify students in a class in need of special attention or 3) to evaluate the effects of different interventions.

Implications for design

Teacher dashboards in digital curricula systems offer a specific opportunity to promote the measurement of student well-being. These dashboards, presently used for reporting on class usage and performance, could offer a powerful channel for reaching thousands of teachers and millions of at-risk students. One potential affordance of these systems is to provide automated recommendations, to teachers or to students that could help measure or support individual or collective well-being.

To illustrate, imagine a student that is persistently struggling within an online learning system (e.g., failing on assessment after assessment). The system could recommend to the teacher to fill out a screening assessment to help identify factors of student well-being that might be barriers to their effective learning progress. The assessment could help a teacher gain empathy and insight into the context and needs of their students. Aggregated, they could help inform administrators about general areas of need, which could help support resource allocation decisions. And, through the same data-driven design paradigm described in this paper, it might be possible to use digital curricula systems to help improve curricular content that could positively influence individual well-being.

It might be advisable to produce a screening assessment that could be delivered to thousands of students. At a class level, this could be used to provide teacher support recommendations and resources. From a measurement perspective, it would be advisable to define student well-being in terms of sleep, exercise, nutrition, social-emotional skills, problem solving skills, autonomy, competency, belongingness, peer relationships, parent relationships, play, emotional traits, etc. Well-being interventions might include various instructional modules, but also interventions like self-efficacy or optimism training, mindful meditation, self-affirmation writing, structured play, etc.

I imagine an ongoing behavioral checklist where teachers could track fluctuations (good days and bad days) and draw inferences about the activities or circumstances that may be affecting student behavior. Further, data from teacher-based observational assessments could be combined with digital assessments to provide a more holistic understanding of child needs and metrics used to measure the impact of any new interventions. Such a system might combine various biological, physiological, and cognitive markers to document evidence-based interventions. These measures would make it easier to identify resources that measurably improve student well-being, such that they could be scaled up to support success in school performance for struggling students.

A number of interventions have been shown to improve psychological well-being (see a meta-analysis by Boller et al, 2013). Further, there is recent evidence that improving student well-being can cause improved academic outcomes. The 2018 Global Happiness Report (Global Happiness Council, 2018), presents data about a new "Gross National Happiness" (GNH) curriculum. Co-developed by the government of Bhutan and the Positive Psychology Center at the University of Pennsylvania, the curriculum targeted 10 life skills in a 15-month course for grades 7 to 12. Well-being, as measured by the EPOCH scale (Engagement, Perseverance, Optimism, Connectedness, and Happiness), significantly increased during the curriculum and remained significant a year after the intervention ended. Furthermore, schools randomly assigned to the GNH Curriculum demonstrated about a full grade level of improved academic achievement. This evidence supports the proposition that "you have to feel well to learn well."

Well-being is also important for teachers. There is multinational evidence (from Bhutan, Mexico, and Peru) that teacher well-being is causally related to student success (Adler, 2016). Clearly, the ability to track the well-being and needs of students and teachers will help educational systems better address those needs and thereby produce improved student outcomes.

A positive future for mitigating the effects of poverty on learning would involve a humanizing culture of continuous improvement. This involves digital products that can measure the needs of high-poverty schools, such that interventions can then be selected to support the most important of those needs. By rolling out new interventions using controlled experiments, a digital learning system can generate causal evidence about the efficacy of the new interventions.

What can go wrong: A cautionary tale from India's implementation of the CCE

This paper describes an incrementalist approach to a complex societal problem: the academic achievement gap associated with childhood poverty (Reardon, 2011). The proposed solution involves systematically measuring the needs of disadvantaged students and then addressing those needs within large-scale learning systems. A key part of the proposed measurement solution involves emphasizing teacher use of formative assessments and non-scholastic assessments. As this has the potential to create new burdens on key stakeholders, implementations of this approach should proceed incrementally and with caution. What follows is a cautionary tale about potentially good policies that are implemented in a non-incrementalist fashion; the moral of the story is to not attempt to "boil the ocean."

In 2009, India passed a constitutional amendment that guaranteed the right to education. In addition to defining educational rights for the first time, this amendment also introduced progressive strategies for assessment. Whereas students were previously subject to a single academic exam in their 10th year of schooling (an exam that would determine their success or failure in school) the amendment mandated that "continuous and comprehensive evaluation" (CCE) be used instead. The rationale was to provide formative assessments at regular intervals that could help teachers respond to gaps in student knowledge. Further, they assessed various academic measures like reading, math, and science but also "life skills," like empathy, problem solving, and coping with stress (Vihar, 2013). Overall, the CCE was implemented with the aim of reducing stress from exams[18], making curricula more "child-centered," encouraging teachers to move away from rote memorization, and promoting a continuous learning loop (Juneja, 2018).

However, the program was discontinued in 2017, due to widespread discontent from students and teachers. While the objective was to provide holistic information that would help teachers respond directly to student needs, the implementation of the program adopted prevailing attitudes towards assessment (Juneja, 2018). As a result, the mandate for formative assessments was implemented as summative assessments: student performance on formative assessments counted for 40% of their total marks. From a teacher perspective, the CCE was just another set of paperwork to complete — and the information collected rarely informed their instruction. The assessments were conducted for accountability needs, but not for understanding student needs. More troubling, teachers had a strong incentive to inflate formative assessment grades: this increased student overall scores and school bragging rights. All of these unintended outcomes violated the intentions of formative assessment, which requires some learning action to be taken in response to assessment feedback.

Why did the implementation fail, despite well-grounded intentions? Notably, this program was rolled out nationwide without a formal pilot (Juneja, 2018). Rather than incrementally

[18]https://timesofindia.indiatimes.com/city/nagpur/CBSE-introduces-Contemporary-Comprehensive-Education/articleshow/20451236.cms

changing behaviors to ensure that the new behaviors aligned to underlying values, the rollout attempted to "boil the ocean." In the process of changing the entire country's education system in such a rapid and revolutionary way, administrators had little choice but to simply expect conformance to reporting requirements, particularly in the context of their existing testing culture. Changes to large and complex socio-technical systems are often most successful when approached incrementally (Lindblom, 1959). This example may help temper enthusiasm for any drastic changes to large educational systems.

Conclussion

This chapter describes how online curricula, used in primary schools around the world, might provide a channel for data-driven continuous improvement methods to systematically identify and incrementally address the needs of high-poverty students. The chapter shared specific data-driven design methods describing how educational systems might incrementally reduce the poverty achievement gap by directing system investments (e.g., design of new curricular materials) towards the needs of high-poverty students.

With empirical data sampled from a US-based online learning system, it was shown that high-poverty schools make use of online learning resources at a similar rate as low-poverty schools. As many digital educational systems disproportionately benefit upper-middle class households, even when available for free (e.g., Khan Academy), it is promising to know that there is relatively equitable access to digital resources in US schools. As expected, the data presented here reveal a strong and linear correlation between school poverty and school performance. The analysis presented then goes beyond this general problem by using online learning system data to identify associations between poverty and performance on *specific* academic topics. This specificity is critical, as it can motivate and inform specific actions for improvement (e.g., improving instructional resources associated with that topic).

After identifying the specific 5th grade math topics with the highest rates of failure in high poverty schools, the analysis then identified the specific math topics that most correlated with future performance (i.e., the end-of-year test); this approach may help prioritize the importance of particular topics for improvement in all schools. It is expected that enhancing performance on these particular topics (which include "decimal place value" and "estimating sums of fractions") would have greater impact on future performance than other topics — however, to prove this relationship, future research would ideally conduct a controlled experiment.

The chapter then described the importance of controlled experiments in a digital educational product. The results help illustrate how online curricula systems might benefit from adopting controlled product experiments; e.g., generate efficacy evidence, optimize student outcomes and contribute to basic research on the science of learning. The analysis showed how experimentation systems might intersect with the development of artificial intelligence algorithms to automatically optimize student outcomes. As these optimization programs are highly dependent upon specific metrics of need, I discussed the importance of expanding school-based assessments to cover other aspects of student needs, namely those that are associated with well-being, poverty, and student academic achievement. Finally, I discussed a cautionary tale of rolling out educational reforms too quickly without regard for the existing culture of instruction.

Digital curricula systems pose several opportunities and challenges to educational science. There is a need to further define a research agenda (i.e., clarify plausible and valuable research questions, identify ethical issues, etc.) to guide future research within large-scale curriculum systems. An underlying driver for these questions is the value of flourishing human development. While the question of values is typically more a question for business, philosophy, and politics, it is interesting the extent to which the cognitive sciences might help inform decision-making about educational goals and underlying humanistic values. Insofar as these sciences plumb the depths of what makes us human, might a field like neuroscience hold hidden insights into the nature of human values? For instance, insofar as neuroscience can characterize human development, might it identify developmental factors that should be given greater priority? "We treasure what we measure;" so, to what extent might neuroscience inform a humanity-centered psychometrics for reliably measuring well-being and poverty?

I wish to highlight the feasibility of using data from online learning programs to enhance performance for struggling students, particularly those in high-poverty schools. Our research group aims to communicate a vision for enhancing social equity by using intelligent feedback loops to systematically improve legacy digital learning systems. This vision is not possible without interactions between scientists, government officials, designers, product owners, teachers, parents, and students. In the context of rapid advancements in artificial intelligence - advances that may transform human society for good or ill - it is hoped this work illustrates practical approaches for integrating humanistic values into intelligent systems.

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12

INTERDISCIPLINARY EXPLORATIONS FOR THE SCALING OF EXPERIMENTAL INTERVENTIONS

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Introduction

When addressing the large amount of information available in digital form on different aspects of human development, one of the critical aspects to consider is how to organize this information in order to answer different questions from different social actors. In this context, visualizations are one of the tools available that contribute to this goal[19]. The computer applications currently

[19] In computer sciences, visualizations have generally been addressed by two communities. On the one hand, those who deal with the interaction between people and computers consider visualizations as the study of technology in itself. Many of the tools that scientists use have been developed by this community. On the other hand, there are those who are involved in developing

available for the development of visualizations allow one to quickly generate maps, charts, timelines, graphics, word clouds, and search interfaces, among others. Neighborhoods, cities, and states are settings in which different types of life events occur for different social groups, and it is precisely in such settings is where human development occurs and where social relationships are built. For example, maps have been a key instrument to identify and solve challenges in the areas of public health (Reich & Haran, 2018), economic development (Klemens et al., 2015) and psychology (Rentfrow & Jokela, 2016).

Some challenges for the design and implementation of these computational efforts in the study of human development are related to the fact that individual data do not necessarily provide information to answer questions that involve processes at different scales (e.g., inter-individual). Furthermore, since each data source contains its own set of errors and complexities, adequate statistical methods are required to integrate information from different sources (Reich & Haran, 2018). However, efforts have begun to produce promising results. For example, Osgood-Zimmerman and colleagues (2018) and Graetz and colleagues (2018) analyzed failures of child growth in different African countries and their relationship to the amount of maternal education. They collected geo-located information on growth retardation, the loss of muscle mass, and weight of children under five years of age and the mothers' years of education, all of them from different surveys carried out in tens of thousands of villages during 15 years. They

graphics, who have largely focused their efforts on hardware to create high-quality visualizations for science and other user communities. The work of both research communities has increased the capabilities of creating visualizations through different developments, such as large-scale immersive environments, high-quality three-dimensional displays, rendering software kits, and visualization libraries.

also combined this data with information on climate and local geography, and validated their statistical model by first fitting it to data from one subset of locations, and then comparing their predictions with data from other different subsets of locations. The authors used their data to identify differences and predictions of improvements over time in different regions, and from this they also managed to specify intervention priorities for early childhood policies.

In another study, researchers and educators from British Columbia (Canada) used the Early Development Instrument (EDI) to assess the emotional, cognitive, language, physical, and social development of children at their level in early childhood education, and thereby examine trends in early childhood development in different neighborhoods and school districts of the city of Vancouver. The developmental risk maps based on EDI data helped to identify vulnerability and resilience factors in child development and local needs for intervention that can help families and communities to promote the healthy development of children before they enter the first grade of primary school. The visualizations generated in this project include maps that can capture different social groups at the community, provincial, and federal levels (Hertzman & Bertrand, 2007).

Another of the instruments that have begun to be designed and implemented with large databases to address public health and human development issues are algorithms that combine different forms of machine learning. For instance, Bansak and colleagues (2018) developed a data-driven adaptive algorithm that assigns refugees to different resettlement locations to improve integration processes in the host country. The algorithm uses machine learning to discover and take advantage of synergies between the characteristics of refugees and resettlement sites. In the first instance, it was implemented with data from the historical record of two countries with different allocation policies and refugee populations (i.e., United States and Switzerland). The simulation approach improved refugee employment rates by 40% to 70% relative to commonly used allocation practices. One of the advantages of this type of approach is that it has the potential to provide different agencies with tools for implementing actions, interventions, and policies that could be quickly applied within existing institutional structures. Likewise, the development of algorithms has also begun to be used in the simulation of interventions aimed at improving aspects of human development. For example, Chittleborough and colleagues (2014) used test effect estimates and structural models from the Avon Longitudinal Study, which includes a population of 11,764 children, to examine the simulated effects of interventions aimed at improving academic skills at the beginning of primary school in educational attainments at age 16 in a context of socioeconomic inequality. The highest intensity interventions showed a 5% reduction in the effects of such types of inequalities.

On the one hand, these type of studies show the availability of theories, statistical methods, and applications that allow analyzing health, education, and development problems at different geographical scales using robust methods and open source software. On the other hand, they also illustrate the importance of combining large databases with specific conceptual and methodological approaches from relevant disciplines such as epidemiology, developmental psychology, economics, sociology, and statistics. The understanding of spatiotemporal processes from such types of interdisciplinary approaches contributes to the design of appropriate and pertinent interventions for different cultures. However, the potential of visualizations in scientific research or in efforts to transfer scientific results to interventions and policies has not yet been sufficiently addressed. This would be associated in part with the fact that visualizations frequently become a final product of scientific analysis rather than an exploration tool. Also, many of the visualization tools available to scientists cannot be updated because they are not associated with databases hosted on the internet, so once they are created they become an immutable information product. One of the reasons for this limitation is that it is difficult to collect scientific data and it depends on specific methods, so the focus of the scientific effort is usually the generation of data rather than its eventual use in applications. Furthermore, many of the scientific problems are related and interdependent and therefore involve data from multiple instruments, disciplines, and sources (Fox & Hendler, 2011).

The capacities that are being generated and used on the internet could contribute to improving these aspects. These approaches are characterized by being user-friendly - which could allow scientists to rapidly generate visualizations to explore hypotheses - and by potentially contributing to visualization scaling. Also, both aspects would permit the generation of new collection and storage approaches to develop and maintain visualizations at a low cost. At the same time, these tools can create challenges that the scientific community must anticipate. First, new approaches are required to determine the best way to visualize scientific data. For example, Lengler and Epler (2020) developed a periodic table of visualization methods that shows different techniques organized by data type and complexity of their application. There are also discussions that propose to change the general principles of effective visualization to those of greater specificity for scientific use, such as discussions concerning the best way to combine statistical methods with visualizations (e.g., Card et al., 1999). Other types of challenges are related to how to create, maintain, and analyze data for visualizations, which implies taking into account the quality of the information, as well as its potential biases and contextual relevance. While significant efforts have been made over the past two decades to address these challenges, further research is still needed to generate scalable solutions that can be dynamically and interactively adapted and updated in the context of the internet.

Visualizations and simulations in studies on child poverty

Risk calculation system

Since the late 1990s, the Unit of Applied Neurobiology[20] (UNA) has carried out research aimed at studying: (a) the associations between child poverty and self-regulatory development (cognitive and emotional); (b) the mediating factors of such associations; (c) the design, implementation, and evaluation of interventions aimed at optimizing the self-regulatory development of poor children; and (d) the transfer of technical knowledge to the design and evaluation of early childhood policies. UNA's work has generated interest in different governmental and non-governmental organizations to explore possibilities for scaling up developmental evaluation procedures, as well as the design, implementation, and impact evaluation of interventions (e.g., Segretin et al., 2014).

In 2011, a national governmental agency in charge of the health of children from 0 to 6 years old living in a contaminated river basin invited a group of UNA researchers to collaborate with the design of developmental assessments and exploration of alternative approaches to address a diversity of developmental issues. Previously, they had implemented a screening test to detect motor, cognitive and language development issues, the results of which showed that 40% of the children evaluated did not reach the

[20] http://pobrezaydesarrollocognitivo.blogspot.com/

minimum levels expected for their age. The projection of this percentage to the child population of the hydrographic basin was 36,000 children. Consequently, this degree of problems revealed the need to expand the approach such that child health referrals were not concentrated only in hospital or community health centers, which in many cases did not have the resources required by some of the issues that needed to be addressed.

Based on contemporary conceptualizations of human development[21] we developed a calculation system that articulates a set of rules and instructions arranged in such a way that their sequenced combination produces a result in terms of a specific referral for a child and her family or caretakers (Lipina et al., 2015). Specifically, given an initial state of risks (i.e., high, intermediate, absent), for different aspects of development (i.e., cognitive and/or motor), temperament[22], and home stimulation for learning, and their combination, a final state (i.e., referral or intervention) is reached that consists of an indication for the child and her parents or caretakers to access a public service that would meet the needs posed by such a specific risk profile (Figure 1).

[21] Characterized by the permanent transformation of the biological and social systems it involves, so that the directionality of the developmental trajectories varies between individuals and populations

[22] In the context of this chapter, *temperament* is defined as the individual differences in reactivity and self-regulation in the domains of emotion, activity, and attention.

DEV	TEM	HOM	INTERVENTION
0-1	0-1	0-1	1 NO INTERVENTION
0-1	0-1	1-1,5	2 HOME STIMULATION
0-1	0-1	1,5-2	3 PARENTAL PSYCHOTHERAPY
0-1	1-1,5	0-1	4 PARENTING STIMULATION
0-1	1-1,5	1-1,5	4 PARENTING STIMULATION
0-1	1-1,5	1,5-2	5 PARENTING STIMULATION + PARENTAL PSYCHOTHERAPY
0-1	1,5-2	0-1	4 PARENTING STIMULATION
0-1	1,5-2	1-1,5	6 PARENTING STIMULATION + HOME STIMULATION
0-1	1,5-2	1,5-2	4 PARENTING STIMULATION
1-1,5	0-1	0-1	7 CHILD PSYCHOTHERAPY
1-1,5	0-1	1-1,5	8 CHILD PSYCHOTHERAPY + HOME STIMULATION
1-1,5	0-1	1,5-2	8 CHILD PSYCHOTHERAPY + HOME STIMULATION
1-1,5	1-1,5	0-1	9 CHILD PSYCHOTHERAPY + PARENTING STIMULATION
1-1,5	1-1,5	1-1,5	10 CHILD PSYCHOTHERAPY + PARENTING STIMULATION + HOME STIMULATION
1-1,5	1-1,5	1,5-2	10 CHILD PSYCHOTHERAPY + PARENTING STIMULATION + HOME STIMULATION
1-1,5	1,5-2	0-1	9 CHILD PSYCHOTHERAPY + PARENTING STIMULATION
1-1,5	1,5-2	1-1,5	10 CHILD PSYCHOTHERAPY + PARENTING STIMULATION + HOME STIMULATION
1-1,5	1,5-2	1,5-2	10 CHILD PSYCHOTHERAPY + PARENTING STIMULATION + HOME STIMULATION
1,5-2	0-1	0-1	7 CHILD PSYCHOTHERAPY
1,5-2	0-1	1-1,5	8 CHILD PSYCHOTHERAPY + HOME STIMULATION
1,5-2	0-1	1,5-2	8 CHILD PSYCHOTHERAPY + HOME STIMULATION
1,5-2	1-1,5	0-1	9 CHILD PSYCHOTHERAPY + PARENTING STIMULATION
1,5-2	1-1,5	1-1,5	10 CHILD PSYCHOTHERAPY + PARENTING STIMULATION + HOME STIMULATION
1,5-2	1-1,5	1,5-2	11 CHILD PSYCHOTHERAPY + PARENTAL PSYCHOTHERAPY
1,5-2	1,5-2	0-1	9 CHILD PSYCHOTHERAPY + PARENTING STIMULATION
1,5-2	1,5-2	1-1,5	10 CHILD PSYCHOTHERAPY + PARENTING STIMULATION + HOME STIMULATION
1,5-2	1,5-2	1,5-2	11 CHILD PSYCHOTHERAPY + PARENTAL PSYCHOTHERAPY

Figure 1 - Risk combination table (green: absence; yellow: intermediate; red: high), at the level of development, temperament and household, and of the possible interventions to implement. The suggested actions are based on interdisciplinary clinical intervention criteria commonly used in pediatric services of public hospitals in the City of Buenos Aires.

This system allows the simultaneous analysis of several levels of risk and suggests a specific solution that can address such needs at the clinical (health center), social development (e.g., child development center), and/or educational (e.g., school) level. Since this system was designed based on a multidimensional conceptualization of human development, it allows the incorporation of data from different types of development assessment tools into its calculation sequence. In their original design, combinations were tested based on the following evaluation instruments, for an age range of 0 to 42 months: (a) level of developmental analysis: Bayley Scale of Child

Development (Bayley, 2015) and Weschler Preschool & Primary Scale of Intelligence (WPPSI) (Wecshler, 2014); (b) level of temperament analysis: short version of the Rothbart Child Behavior Questionnaire (Putnam & Rothbart, 2006); and (c) level of home analysis: HOME Inventory (Caldwell & Bradley, 1984). Finally, to determine the different interventions, pediatric clinical and psychopedagogical criteria commonly used in pediatric hospitals in the City of Buenos Aires were used.

Computational explorations

Once the collaboration with the governmental agency ended, we began a new stage of explorations of the calculation system together with researchers in the area of computer science. The aim of such explorations was to improve the understanding of the study of self-regulatory development and its modulating factors with and without the implementation of interventions aimed at optimizing it, based on the use of different concepts and computational tools.

Below we show some examples of visualizations developed with the aim of improving and making more complex the observation of data from research carried out at UNA, in studies with children between the ages of 4 and 8 years from different socioeconomic contexts and cities in Argentina. As in the case described in the previous section, the same indicators were used for the levels of analysis (i.e., cognition, temperament, and home stimulation), and risk levels (absent, medium, and high for the colors green, yellow, and red, respectively) defined based on comparing the value obtained for the indicators with that expected for the context of each child. It is important to clarify that such aim does not imply that visualizations replace statistical methods that allow quantifying the observed effects, but rather contribute to developing intuitions and new hypotheses that could eventually be statistically evaluated.

Sankey diagrams

A Sankey diagram is a visualization that allows representation of the development of participants of a research study with longitudinal design to be observed over time. The diagrams in Figure 2 allow the verification that the performance trajectories through the evaluation rounds have had a variable development between individuals, generating a new exploration opportunity aimed at identifying factors that could be associated with such variations.

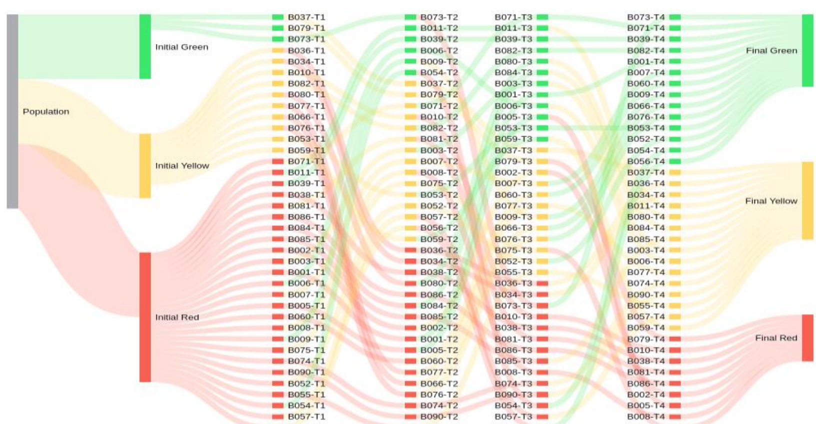

Figure 2 – Sankey diagram showing the development of cognitive performance of a group of children aged 3 to 5 years from an intervention study (longitudinal design) carried out in the city of Buenos Aires (Segretin et al., 2014). Each alphanumeric code represents an individual participant. Each column is an evaluation round. Color sets represent risk status at the start (left) and end (right) of the study.

An alternative interest for this type of visualization is the possibility of involving an interactive phase that, given the actions of a user -for example, a researcher interested in analyzing the impact of interventions aimed at optimizing children's cognitive development- can extract more specific information from a dataset. In this sense, Sankey diagrams are exploration tools that can select trajectories of particular individuals (Figure 3) or groups of individuals (Figure 4) which is achieved by placing the mouse cursor over a particular trajectory.

Although these visualizations do not contain information about the causes that explain why each individual or group has such different trajectories, it allows us to explore the occurrence of these phenomena. The causes of such diversity in the development of trajectories should continue to be explored; but individual or group development can be quickly consulted and observed with this tool.

Figure 3 - Sankey diagram showing the development of cognitive performance of the same children as in Figure 2. This case illustrates the selection of a single path that starts from a high risk level and reaches a low one at the end of the study. Identification of a single path is done by putting the mouse cursor over it.

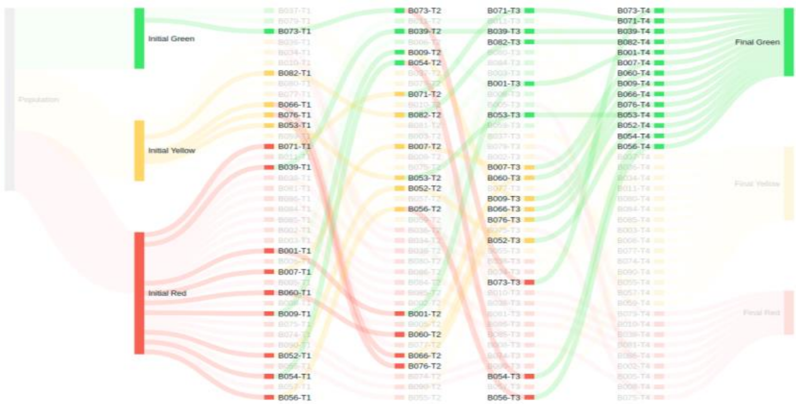

Figure 4 - Sankey diagram showing the development of the performance trajectories of all the participants who ended up with no risk (green) and who started from different risk levels (green, yellow and red).

Risk states and simulations of interventions

Another visualization we developed allowed us to explore the makeup of the population of children who participated in the aforementioned study. In other words, we continue to consider the dimensions of cognition, temperament, and home stimulation. Each risk combination configuration of these three levels represents a state (e.g., green cognition + yellow temperament + red hearth versus yellow cognition + yellow temperament + yellow health), which permits the analysis of the distances between different states, as well as their similarities and differences based on different theoretical aspects of the combination of risks at different levels of development. One possible way to approach such analyses is by establishing relationships between possible states and defining whether two states are closer if they differ by one level, with a single adjacent color change (e.g., from red to yellow, or from yellow to green, but not from red to green). These types of definitions could contribute to the identification of a particular risk association structure for a specific population.

For example, Figure 5 shows the combination of risk states of the three levels corresponding to the population of children in the Segretin and colleagues (2014) study, represented by united circles. In this case, the opacity of each of the states was added to indicate the number of individuals in this state. In this figure it can be seen that: (a) the most frequent states are red + green + green and the variation of the household level to yellow and red; (b) there are combinations that are not observed, such as red + red + red; and (c) there are no combinations that have the temperament level in the red state.

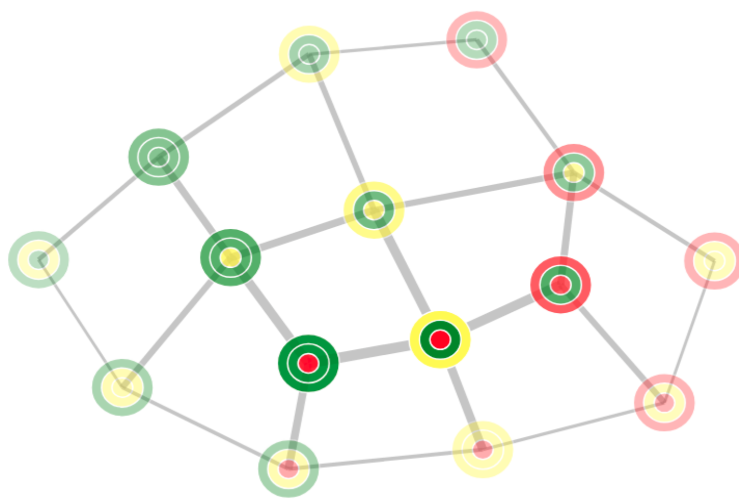

Figure 5 – Example of a network of risk states for cognition + temperament + home levels, of children from Segretin and colleagues study (2014).

Another interesting aspect of this visualization is that it can be used to simulate interventions and thereby analyze state changes. In the context of this section, we define simulations as calculations and operations that emulate what could happen under certain conditions over time. The latter requires theories of change for each level of analysis and their combination, on which we do not necessarily have evidence. In such a context we can apply assumptions based on statistical criteria, from clinical practice, or by making hypothetical assumptions based on the knowledge available in developmental science. For example, if we assume that the risk can be changed one level at a time, this would allow decisions to be made concerning at which level it would be necessary to invest intervention efforts and thereby promote the desired change of state. In an ideal scenario in which every investment is possible, the goal would be that all the states of all the children end in green for all the levels (cognition + temperament + home stimulation). However, this is not usually the case, so this type of visualization tool could contribute to identifying different subgroups of states that would have different intervention needs and priorities. For example, in a subgroup characterized by a state of green cognition + green temperament + red home stimulation, the priority could be to carry out interventions aimed at optimizing home conditions. The costs to generate changes at this level would be significantly higher and difficult to achieve compared to another characterized by green cognition + yellow temperament + green home, which could consist of working with short-term parental guidance strategies. In any case, these types of visualizations could contribute to efforts to identify subgroups with different intervention priorities. It is important to note that in the examples presented here only the cognition, temperament, and home stimulation levels were used. To the extent that researchers include other dimensions and levels, they could involve other types of tools and theories of change.

In the area of simulations there are different alternatives to explore, the choice of which must be adjusted to the research or policy objectives. One such alternative is to assume that each individual is an intelligent agent, defined as an entity that has a possible repertoire of actions that can result in profit or loss. In such a modeling process, agents need to be defined in terms of their characteristics. In the current example, an individual would be represented by the indicators of cognition, temperament, and home stimulation, each of which could take the values of green, yellow, and red. On the other hand, it is necessary to define the actions of each individual, which could eventually be defined as action 1, action 2 ... action n. However, in the current example, it is difficult to define such actions because it is not possible to anticipate the actions of each individual and the eventual gains or losses (e.g., changes in temperament or home stimulation due to interventions are not changes that depend solely on, or necessarily from, the actions of an individual). This implies that the nature of the data conditions the possibilities of implementing simulations, so in cases like this it is necessary to implement other strategies.

An alternative strategy we explored was to define probabilities of change of states. For example, taking a single level (e.g., cognition), and the criterion that there can only be a change from one level to an adjacent level, an individual or group of individuals whose current state is defined as yellow, in the future - for example, after an intervention - it would have three possible scenarios: green (improvement), yellow (remains in the same state), or red (worsens). In our exploration, we define different types of probabilities for each transition. In the example presented in Figure 6, the probability of staying in the green state is 70%, while the probability of going to the yellow state is 30%. This means that if we simulate 100 changes, an individual whose initial state is green 70 times would stay green while 30 would turn yellow. The same occurs in the yellow state, which has a 50% chance of remaining yellow, 30% going to the green state, and 20% going to the red state. With these types of rules it is possible to see the evolution of a population over time. Different types of probabilities would lead us to different patterns of development, so that some changes would be more pronounced while others slower.

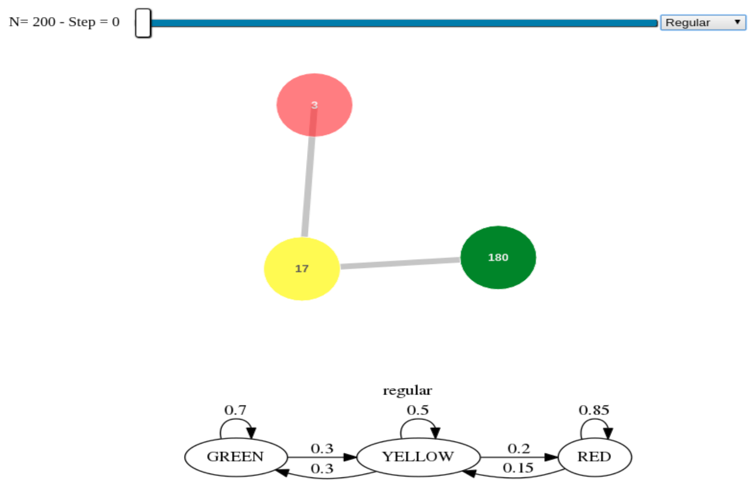

Figure 6 - Example of state change probabilities in a computer simulation context for an organization level (i.e., cognition).

The challenges for the use of this alternative are determined by several factors: what the probabilities are, how they could be modified through interventions, and what would happen in each individual or group over time. Such information is what should be considered to inform the different theories of change of the dimensions or levels to incorporate in the analysis. Likewise, this simulation tool can be used to address more complex problems involving more levels that represent different dimensions of analysis, which in turn may or may not be modified based on different types of probabilities. This poses a new challenge since it implies more definition requirements. For example, in the case illustrated in Figure 7, in which 3 levels are used, it is necessary to have the definition of 21 probabilities (3 metrics x 7 transitions), which raises the possibility of carrying out many tests, but also the difficulty of defining which values to incorporate in the model.

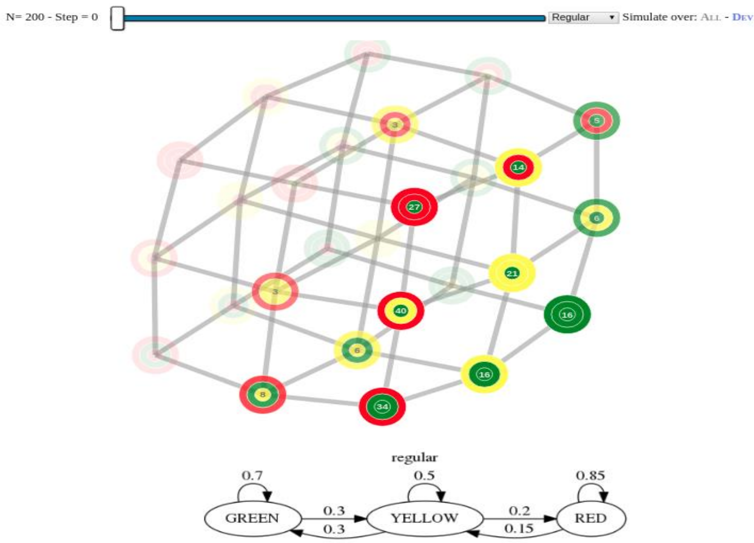

Figure 7 – Example of state change probabilities in a computer simulation context for three levels of organization (i.e., cognition, temperament, home stimulation).

In summary, the testing of different models and probabilities would contribute to the replacement of intuitive approaches by those in which it would be possible to validate hypotheses about the change of states of specific populations over time or by interventions.

Geolocation

Another type of visualization we explored was one constructed from the place of residence of children, in order to be able to observe trends and regularities in the states and changes of states over time of the levels of cognition, temperament, and home. An example of such an approach can be seen in Figure 8.

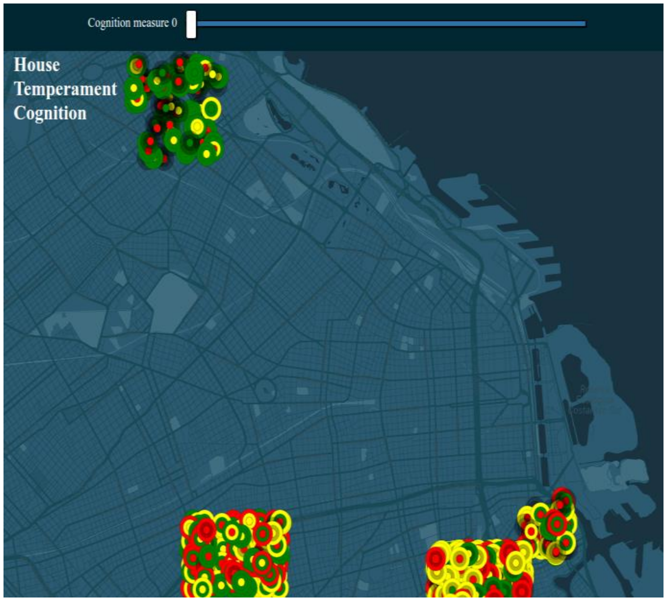

Figure 8 – Example of geolocation of risk states for levels of cognition, temperament and home stimulation ("house"). Each set of three rings represents a child and the location of their home on the map of the city of Buenos Aires. At the top can be seen a status bar that can be moved to the right to check the status of changes as a result of interventions. The data correspond to the study by Segretin and colleagues (2014).

When observing the map as a function of the three levels, some regularities are observed that would allow distinguishing subpopulations in two regions of the territory (i.e., the risk levels in the north of the city are lower than those in the south). Furthermore, by selecting one level at a time it is possible to show that: (a) the level of temperament risk does not vary in the three neighborhoods analyzed; (b) the level of house risk is lower in the north of the city, according to expectations based on the socioeconomic distribution of the population; and (c) the level of cognition risk shows more variability within each of the neighborhoods.

Conclusion

As information technologies allow researchers to develop visualizations that contribute to improving the understanding of the problems under study, they may begin to think of them less as a final product and more as a complementary tool to build knowledge. This requires researchers to use visualizations from the early stages of an investigation, documenting the relationships between them and the data. Consequently, for these purposes it is necessary to foster dialogue and collaboration between researchers from different disciplines and computational scientists to ensure that the needs of the development of new analytical methods are met and to explore generalizable forms of scalability.

In addition, frequent use of visualizations in research work could improve requirements for the design of new tools, as well as learning to share and maintain workflows and visualization products in the same way that other scientific knowledge is shared. A side effect of these efforts could be reducing costs and increasing accessibility, to generate more sophisticated visualizations of increasingly large datasets.

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13

REFLECTIONS ON THE DEVIATION OF ATTENTION TO POVERTY IN THE EARLY CHILDHOOD DEVELOPMENT AREA

Helen Penn

Introduction

I started my professional career a long time ago as a psychologist, with a dose of rats and behaviorism, but first became a teacher for young children and then an organizer and director of educational and childcare services, which eventually led me to dedicate myself to the design of early childhood policies for the European Union (EU) and the Organization for Economic Cooperation and Development (OECD). My arrival in the academic world was relatively late in my professional career. I could say that my specialty is early childhood education and care (ECPI) services, which are currently an important aspect of education provision in the EU and specific to the OECD. In addition to working in Europe, and to a lesser extent in North America, for the past 15 to

20 years I have worked in developing countries, mainly in South Africa and Central Asia. In these regions, I became involved in the design and implementation of large-scale aid programs, working on early childhood development issues for a variety of international agencies, and later for UNICEF.

The EU guidelines for member states is that 33% of children aged 0 to 2 years and 95% of children aged 3 to 5 should have access to such provision. In its family database, the OECD offers comprehensive measures of service utilization and relevant family support. Therefore, ECPI services are widespread and are now an integral part of the lives of most families in industrialized countries. These services are provided for the most part on the basis of the rights of children and women, as well as evidence-based effectiveness. In this context, a central question in my analysis is how this generalized service, which sometimes covers ten hours a day for a young child, affects the millions of children and parents who use it; and how the hundreds of thousands of employees who work in such services do their jobs.

Development aid is intended to help poor countries accelerate their development through appropriate advice, technical expertise, and provisional aid. Given this assistance, they are expected to reach the same levels of development as richer countries. Recent economic data provided by the Global Financial Integrity organization suggests otherwise. They show that for every $1 in aid, $24 is drawn in terms of resources, debts, patents, trade agreements, and various types of money manipulation. In light of these figures, it is questionable whether the aid could be interpreted at least in part as a possible cover for the exploitation of poor countries. One of the central problems, from the socioeconomic point of view, is not only the deficiencies of poor countries or the difficulties that children face in developing their full potential, but the extremely unfair world in which these countries must operate. In this context, it is important to analyze the proposed financial practices from the industrialized countries. The truth is that there is a sophisticated debate around aid policy and economy, but most academic commentators agree that aid is highly problematic in its effectiveness, despite the optimistic description of the agencies that promote it (Chang, 2007; Collier, 2008; Ferguson, 2015; Hickel, 2017; Hulme, 2015; Illingworth et al., 2011; Kwon & Kim, 2016; Milanovic, 2016; Singer, 2010).

Many international aid agencies do not refer to these troubling aspects of the debate on the nature of development aid. More frequently, such agencies have promoted the intervention movement in which they include rhetoric that explicitly states that such efforts are based on evidence provided by neuroscience. The idea of the stimulation and nutrition programs for children to "develop their brains" has been adopted and promoted by international organizations around the world concerned with children and their future. (e.g., UNICEF, World Health Organization, World Bank). Such interventions, it is predicted, will make a huge difference not only for children and their families but also for the well-being of their countries.

A recent example of one of these narratives is the World Health Organization's International Child Development Steering Group series, published in the prestigious medical journal The Lancet. The series is titled *Advancing Early Childhood Development: From Science to Scale*. The various authors participating in such a series point out that millions of children are at risk of premature death, developmental disorders, or pathologies due to conditions that could be prevented through improvements in their early development. Building on the microeconomic analysis proposals made by the American economist James Heckman based on longitudinal interventions carried out with ethnic minorities in the United States, it is proposed that it would be more efficient to invest early in child development than to financially compensate the consequences in adulthood for early exposure to adversities associated with social inequity.

The Lancet series is defined in this way: "*This series considers new scientific evidence for interventions, building on the findings and recommendations of Lancet's previous series on child development (2007, 2011), and proposes pathways for implementation Early Childhood Development at Scale. The series emphasizes "nurturing care," especially for children under the age of three, and multi-sectoral interventions that start with health, which can be wide-ranging for families and young children through of health and nutrition*" (Black et al., 2017). The goal of reducing suffering and improving children's health is absolutely necessary and admirable. However, the assumption that actors outside a developing country implement a specific early intervention program, that its application will improve the performance of that country in the long term, and that this contributes to somehow changing the balance between industrialized and developing countries, it is at least questionable in light of the macroeconomic figures.

Among other factors, such a proposal would not be considering central aspects of the work of organizations such as the OECD carried out during the last decades on the nature of planning and organization of services for early childhood. In particular, it would seem to be unaware of the accumulated experience regarding the content of such programs, as well as aspects related to the people who implement them. The question arises whether this could be due to the fact that the experiences and standards of industrialized countries are not considered as development objectives or relevant experiences for developing countries. For this, it would be important to address the complexity of the developmental contexts of different cultures of peripheral and central countries. In this sense, two important aspects of the work carried out in this field are the analysis and understanding of the broader political, economic, and social contexts of the lives of children who participate in any early intervention. For example, the OECD Family Database[23], which is compiled from international statistics on demographics, family structures, levels of income, and income support, as well as patterns of education and care and child wellness services, offers a complete picture of the life of children. In addition, the Young Lives project[24], which investigates the lives of 12,000 children over a period of fifteen years, aims to provide a similar overview. This more comprehensive picture or references to the context of children's lives is absent in the Lancet series.

On the other hand, the assumption that neuroscience has identified the mechanisms underlying the impact of early adversity on child development, and that this justifies technical remediation approaches, could also be considered questionable. In my view, such assumptions have been forged in a specific cultural context that positively values socioeconomic individualism.

The uses of brain science

The argument presented by important agencies such as the World Bank (Young & Mustard, 2008), WHO (Maggie et al., 2005), and UNICEF could be summarized as follows. Fostering child development through both physiological (e.g., nutritional supplements) and intellectual "stimulation" will contribute to the promotion of more productive citizens who will be able to better collaborate with the future prosperity of their country. This proposal has been expressed in a variety of documents and in prestigious academic publications such as The Lancet (Black et al.,

23 http://www.oecd.org/els/family/database.htm
24 https://www.younglives.org.uk/

2017; Chan, 2013, Engle et al., 2011; Grantham-McGregor, 2007) and The Economist (2014). For example, a recent UNICEF publication (2014: 1) titled *Building Better Brains: New Frontiers in Early Child Development* states that acting on the findings of neuroscience "*it will have important implications for the future of millions of the most disadvantaged children and their societies*."

The neuroscientific findings, in an informal first reading, seem to suggest that promoting brain development through early stimulation would be the reason why early intervention would work. One of the most cited researchers in this field is the Canadian Fraser Mustard, whose work has been referenced by different groups of early childhood experts from the United States (e.g., Brookings Institute; World Bank) and Canada (e.g., McCain Foundation). Their contribution is synthesized in an article by the Brookings Institute titled *Early Development and Experience-Based Brain Development: The Scientific Foundations for the Importance of Early Childhood Development in a Globalized World* (2006). In this publication Fraser Mustard states that "*To achieve the objective of improving the competition and quality of our populations, and to establish sustainable, stable, equitable, tolerant and pluralistic democratic societies, we must find ways to optimize human development, health and well-being in all regions of the world. Continuous evolution and improved function of our brains will influence how we face the challenges and opportunities we face today. To do this, we must understand the development of the brain and its continuous evolution and how the experience in early life affects its development*" (2006: 47). It also proposes that since developing countries cannot provide early intervention programs on their own -for reasons not mentioned- international agencies should intervene: "*Societies in the developing world will not be able to make investments to ensure a good early childhood development unless international agencies like the World Bank, United Nations and other international organizations provide more support and leadership. One needs to ask the question within these international* *agencies: "Why is there a gap between what we know and what we do?" If we do not close this gap, there is a high risk that, given the conditions of today's world, a substantial failure will occur to improve the competition and well-being of populations and to improve equity, which could put our societies and the experiments of civilization at risk.* " (2006: 47).

The analogy used, especially by those concerned with the health and well-being of young children, is that just as the growing body benefits from a wide range of micronutrients, the growing brain needs external stimulation -although the systematic exploration of what constitutes "stimulation" in very different societies is largely unexplored. For the most part, these early intervention programs are directed at "the first thousand days" of the child's life. The increases in synaptic connections that have been observed under laboratory conditions in the developed world, in response to controlled stimulation events, would be taken as a guide for programming and expansion. In this sense, Bruer (2014) has shown how the findings of neuroscience have been exaggerated when applied to the field of early childhood development. Rutter and Solantus (2014) call this process "translation gone awry". Neuroscientific findings on brain development in young children can contribute to highly specialized neuroscientific discussions of brain architecture, or of the methodologies and equipment used to analyze brain function. However, the transfer of such knowledge is more problematic. In this sense, it is important to maintain a cautious position: highly limited and specialized findings cannot necessarily be extrapolated to make general prescriptions on social policy.

Many neuroscientists point out the extraordinary complexity of the central nervous system. For example, we only have a rudimentary knowledge about the functioning of the brain within the even more complex phenomenon that is the body (Gianaros & Wager, 2015). For example, brain development is closely related to neuronal and hormonal development of the intestine in ways that are minimally understood (Allen et al., 2017). Our limited understanding of the brain as an organ cannot be extrapolated to present an image of a thinking and active human being. However, these limits to our current understanding are frequently unknown in public communication of neuroscientific evidence. For example, a report from the McCain Foundation includes a diagram of the brain with the caption: "*The brain as the basis of the human mind. In this diagram, an executive "mind" assigned to the brain assigns functions to "create, reflect, respond, dream, love, express, amaze, do, and learn to act*" (McCain et al. 2011: 53).

Socioeconomic individualism

One of the arguments for the use of neuroscientific evidence in the field of early intervention argues that it could support the economist James Heckman's hypotheses about early intervention (Heckman & Masterov, 2005). This Nobel Prize-winning economist has argued that if some kind of corrective action is to be taken regarding the early impact of adversities affecting children, it is more effective to do so in the early stages of development. His work in the field of microeconomics was originally based on the exploration of statistical validity and the generalization of small data sets. In one of his studies, he carried out an analysis of three early interventions with longitudinal design and randomization of controls, in themselves problematic (Penn et al., 2006), which is located within a particular theoretical framework on family functioning and its economic consequences. This framework holds that individuals are responsible for their own development and prosperity, and that structural inequalities are relatively unimportant. Consequently, individuals and families have to accept their circumstances and equip themselves to face it and prosper in the modern globalized world. Their prosperity and competitiveness depend on it.

In this scenario, the family, instead of being a target for structural change or service provision, is the place for improvement. James Heckman and Gary Becker (another Nobel Prize winning economist) have based their economic predictions on a particular analysis of family functioning. In this calculation of accounts, people living in poverty would be responsible for their own deficiencies, so it turns out that the family is the main producer of the skills that are essential for educational and work success. Unfortunately, many families cannot adequately perform this task, which slows the growth of the quality of the workforce. Families are defined as dysfunctional and are also an important determinant of the participation of children in crime and other pathological behaviors that generate high costs for society. In this framework, the logic of investment in early childhood exposed to poverty is based on criteria of future productivity.

In this analysis, the family, and especially the mother, is responsible for instilling in their sons and daughters the skills and attitudes necessary to face a competitive environment and become prosperous in the long term. All other mechanisms and supports for individual human development are considered minor compared to the fundamental role of the individual's family. From this perspective, many children would be at a disadvantage because their mothers do not create the right kind of environment to help them develop the right skills and attitudes. In these cases, to avoid further damage, the proposal is for the state to intervene. If this occurs, such intervention is likely to be more effective when children are young. This perspective takes inequality for granted, naturalizing it. Inequality can be reduced by better equipping the poorest children to cope with the situation, through early educational intervention. The least needy parents can buy the services they need in the private market.

Heckman's argument is that microeconomic analysis shows that the effectiveness of interventions with the poorest families has been demonstrated through randomized design interventions (i.e., Perry High Scope, Abecdarian, Chicago Child Centers). His argument is both statistical and political. Early intervention will save money, because it is cheaper to intervene early rather than spending money to remedy the impact of poverty on child development through education or incarceration -these costs were estimated based on what happens in the educational and prison systems in the United States, which is not easily generalizable to other countries.

Other aspects that are important to consider are the characteristics of the studies on which the results are based and their interpretations. All of them were carried out with populations of children belonging to ethnic minorities (i.e., African-Americans and Hispanics). They differed in their target populations, in the age of the involved children, in the duration and intensity of the interventions, and also in the results. On the other hand, they were carried out at a historical moment when segregation and discrimination towards the involved minorities was naturalized -a factor that was not taken into account or was minimized in the analyses. Heckman, as an economist, acknowledges that the exact nature of educational intervention is beyond his grasp, but his position assumes that there are experts, technical educators, who can diagnose poor learning and correct it. In his opinion, there is proven experience in implementing early intervention programs at scale and measuring their results.

Many have assumed that Heckman's ideas are underpinned by neuroscience. In fact, what has happened in some sectors dedicated to early childhood development is the fusion of economic arguments with the interpretation of the neuroscientific evidence previously discussed. In such rhetoric, the efficacy of early intervention seems to be confirmed by ideas about rapid brain growth in the first years of life and vice versa. The rationality about why the intervention is effective would be because the brain is more flexible and malleable, and is busy forming the synaptic connections that are the foundation of learning when children are very young. In this sense, Heckman and neuroscience have been seamlessly connected. Many agencies have adopted the slogan of the first thousand days based on these notions as a guide to formulate early intervention programs.

Cultural hegemony

The arguments about brain stimulation are not new, especially in low-income countries. For example, in 1955 Maistriaux wrote the following: "*The black boy has no toys. He finds no opportunity around him to stimulate his intellect ... Blacks' early childhood always takes place in an environment intellectually inferior to what is imaginable in Europe ... The black child remains inactive for long hours. Therefore, he suffers a terrible reduction in his head from which it is practically impossible to recover. The neural centers of his cortex, which should normally be used for exercise, do not receive the necessary stimuli for its development*" (Maistriaux, 1955, quoted in Erny, 1981: 88).

This quote is over sixty years old, although in content it is not very different from some other contemporary ones about brain contraction and the need for stimulation. It was taken from a French colonial text published in 1955. There are many such colonial and religious references to the brains of Africans, which constitutes an ideology that reaches its peak in apartheid in South Africa. It is an important sign of progress that no serious contemporary analyst makes comments based on the skin color or ethnicity of people living in poverty. However, it is possible to ask whether or not poverty and low income have replaced ethnicity in some rhetoric as a marker of insufficiency and necessary intervention.

The central idea contained in the colonial extract is that the environment in which poor children grow up in low-income countries is intellectually inferior. This idea of lack or deficit, compared to Euro-American standards of early childhood education (i.e., middle class) could be implicit, at least in part, in the literature on early intervention promoted by international agencies. Much of the research in the area of early intervention is derived from low-income families in the United States. Their situation is supposed to be similar to that of children in low-income countries in general. For example, a major review of early stimulation programs by Baker-Henningham & López-Boo (2010) for the Inter-American Development Bank does not make any distinction between the circumstances of very poor children in the United States and those of different low-income countries such as Peru, South Africa, Jamaica, and the Philippines. The assumption of early intervention advocates is that the brain is an organ that develops (or does not develop) in the same way in all children, and therefore the same type of early stimulation would apply equally in different societies.

These science-based stimulation prescriptions often inform the work of agencies that provide early childhood development programs in low-income countries. This includes standard interventions based on the Western rationality for societies where it could be understood differently; as well as activities such as shared reading with young children in poor communities where books may not be available or even be unknown, or illiteracy rates are high. Frequently, indigenous ideas or assumptions about parenting, peer games, participation in their families' working lives, multilingualism, dance, or art as a means of expression or spirituality, well-being, and multiple facets of cultural diversity and wealth are simply ignored. Instead, the interventions are mostly low-cost, home-based, and assumptions about the nature of the stimulation or about material possessions that families do not necessarily have.

The lack of awareness of any cultural difference or circumstance between people living in poverty in the United States and those in other countries is surprising, given the significant body of work in cultural anthropology available today. Even leaving aside all possible political analyses of poverty, many early childhood researchers have tried to draw attention to the importance of considering the beliefs and cultural values of different societies (Nsamenang 2008; Penn 2012). For example, Bruner (2008), Gottleib (2004), LeVine (2003), Serpell and Adamson-Holley (2015) and Correa-Chávez, Rogoff and others (2016) have detailed the cultural values and approaches that shape the learning of young children, the myriad of ways that children learn, and the tools that shape their learning. These authors underscore the importance of local contexts and knowledge in raising children. For example, LeVine summed up one of the key aspects of cultural differences as follows: "*Compared to Africans, American babies experience a particularly clear distinction between situations in which they are alone and those in which they are with others, since African babies are never alone and often present as nonparticipants in situations dominated by adult interaction, the American infant is often kept in solitary confinement when not in the adult spotlight. This creates (for Americans) a bifurcation between the extremes of isolation and interpersonal arousal that is unknown in Africa; and that it may be the basis of some of the surprising differences in the interactive style between the peoples of the two continents*" (2003: 82).

However, this literature is rarely referred in the scaling proposals for early interventions. In such a context of thought, it is worth considering whether an eventual omnipresence or overvaluation of ideas about brain stimulation has generated at least in part that agencies overlook such aspects of cultural differences in parenting and child stimulation.

Gender inequality

Early intervention programs in low-income countries have tended to focus on various types of home visits to teach mothers how to stimulate their children and "grow their brains". A significant portion of the programs reviewed in the Lancet series, for example, fall into this category. Such programs have the advantage of being very cheap, compared to any type of service provision, as well as including little that is challenging compared to other policies. However, some of these approaches have supported unproven assumptions about mothers or caregivers' availability and willingness to participate (e.g., Sammans et al., 2016). In addition to the instrumental view of children's performance to manipulate their development (which in itself could be ethically problematic, Morrow, 2013), a striking aspect of early intervention research is the relative lack of voice of the mothers and families who are their target. In such a context of analysis, the question could be raised as to whether such studies would generate any kind of inequity to the detriment of women. For example, it would be important to start analyzing whether economic or neuroscientific approaches do not adequately recognize the contribution of women through unpaid care work, or the burdens that poor women face (Bakker & Silvey, 2008; Razavi, 2011).

Mothers and caregivers can cooperate openly, but they can also tacitly express their disagreement simply by absenting themselves. Very few early intervention projects report participation rates. However, there are some indicators that suggest that the participation rates of mothers, caregivers, and home visitors in these early intervention programs are much more erratic than those generally accepted (Penn, 2015). Even in the Perry High Scope early intervention program, included in James Heckman's analyses, home visitors were nearly unable to complete their regular visitation program (Penn et al., 2006). In the reports summarized in The Lancet, it is difficult to find information on the sampling, participation and loss rates of participants, both from home visitors and from those who are supposed to help with child stimulation activities.

Women's care responsibilities and the impact on their lives and those of their sons and daughters affect poor women more than wealthier professional women. Women with reasonable incomes can rely on hired domestic staff and other forms of domestic help. Women who do housework, by contrast, are often internal or external immigrants who may even neglect or abandon their own sons and daughters to earn a living caring for the sons and daughters of other women (Heymann, 2003, 2006; Hothschild & Ehrenreich, 2003; Rahazvi, 2011a, 2011b). Recent work by Samman et al. (2016) suggests that women have particularly suffered from rural-urban internal migration within poor countries, and that they can be described as "new poor". Women, often alone, with disorganized family networks and heavy jobs in the informal sector (e.g., domestic staff, informal vendors) struggle to support their sons and daughters. Under these circumstances, Samman and others suggest that approximately 35 million girls and young boys worldwide are left alone or cared for by their siblings, in dangerous situations, in slums or insecure areas, while their mothers work. UN Women (2016) has also highlighted the need to take into account the complex situation of mothers and caregivers who experience these circumstances in any intervention program.

Conclusion

Cognitive neuroscience is a frontier discipline. It is fascinating, and it has great power and potential to offer us explanations of child development. The knowledge that I have learned during my participation in the course on neuroscience and poverty at the International Mind, Brain, and Education School is cutting edge. However, I have heard about small-scale studies. In that sense, I ask myself whether the findings are robust enough and free of contextual influences to be transferred from Pittsburgh or Pennsylvania to Harare or Tashkent. Precisely, these are the kinds of claims that international development agencies frequently make when considering neuroscientific evidence. I still consider that multidimensional and complex higher order concepts, such as poverty, inequality, or culture, require other levels of analysis; and that national borders are not easily crossed when it comes to implementing interventions. If we are to have useful information about the roots of poverty, then, as Michael Rutter says, we must be very careful about how scientific knowledge is transferred to the design and implementation of interventions. We have to make sure that we are not inadvertently doing more harm than good by the way we focus our attention and make our proposals.

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GLOSSARY

Amygdala. A set of neuron nuclei located deep in the temporal lobes, which receives and sends multiple connections to different areas of the brain and is involved in different aspects of emotional and learning processing.

Apoptosis. Process of programmed cell death.

Axon. Neural cell projection extending from the cell body, mainly involved in sending a signal from the cell body to other neurons, as well as organs and muscles in the body. At the end of each axon are synaptic vesicles, which contain different types of molecules called neurotransmitters. The nerve impulse consists of electrical changes in the membrane potential of neurons, which travels from the cell body to the synaptic vesicles through the axon. These electrical signals cause the synaptic vesicles to release their contents into the synaptic space, or gap between two neurons, transforming the signal from electrical to chemical. Once in the synaptic space, neurotransmitters bind to receptors on the next neuronal cell, eventually initiating a new cycle of electrochemical transmission.

Cerebral cortex. Gray matter (see definition in this Glossary) that covers the surface of the cerebral hemispheres.

Cortisol. Steroid hormone produced by the adrenal gland as a result of stimulation of adenocorticotrophin, which is released in response to stressors in the form of glucocorticoids. Its functions include increasing blood sugar level, suppressing some immune system functions, and contributing to the metabolism of fats, proteins, and carbohydrates.

Dendrites. Branched extensions of neuronal cell body, mainly involved in receiving nerve impulses from other neurons.

Cell differentiation. Process by which embryonic cells acquire the morphology and functions of a specific cell type.

EEG / ERP. Techniques for the study of neural physiology based on the recording of brain bioelectric activity under different conditions. An electroencephalogram (EEG) detects ongoing electrical activity, recorded from electrodes placed on the surface of the scalp. Event-related potentials (ERPs) are derived from the EEG and reflect activity time-locked to the presentation of a particular stimulus. An ERP is created by averaging the electroencephalographic activity in response to multiple instances of the presentation of specific -auditory, visual or somatosensory stimuli. Both EEG and ERP techniques have limited spatial resolution, since they do not accurately detect the place where neuronal activity originates, but particularly ERPs have high temporal resolution that allows neural responses to events to be defined in the millisecond range.

Epigenetics. Discipline that studies the set of mechanisms that modify the activity of DNA, such as its expression, but that do not alter its sequence.

Executive functions. A set of cognitive abilities necessary to control and regulate thinking and behavior, such as establishing, maintaining, monitoring, correcting, and achieving a goal-directed action plan.

Head Start. Program of the United States Department of Health and Human Services that provides comprehensive early childhood education, health, nutrition, and parent services for lower-income children and their families. The program's services and resources are designed to foster stable family relationships, improve children's physical and emotional well-being, and establish an environment for the development of cognitive skills (more information available at the following link: https://www.nhsa.org/why -head-start / head-start-model).

Hippocampus. A complex neural structure with connections to and from multiple networks distributed throughout the brain. The hippocampus is involved in all processes of memory, learning, and spatial and emotional cognition.

HPA axis. The hypothalamus-pituitary-adrenal (HPA) axis is activated when a person encounters a perceived stressor and prepares to act, and also contributes to adaptation to an environment perceived as threatening. When the system is activated, the hypothalamus circulates corticotrophin-releasing hormone, which upon reaching the pituitary gland activates the release of corticotropin. When the adrenal cortices (located above the kidneys) receive corticotropin, they in turn release different types of corticosteroids, which act on the brain and in particular the frontal cortex, hippocampus, and amygdala, all of which are related to emotional and cognitive self-regulation.

Interspecific. Relationships established between different animal species.

I.Q. The intelligence quotient (IQ) is a score derived from standardized tests designed to measure human intelligence. Historically, IQ was defined as dividing mental age (obtained through intelligence tests) by chronological age, multiplied by 100, such that a score of 100 represents average intelligence for a given age.

Methylation. Epigenetic mechanism by which methyl groups are added to DNA and which is associated with the regulation of the inhibition of gene expression, without altering the DNA sequence.

MRI/fMRI. Neuroimaging techniques that produce high-resolution images of the location of brain structures (MRI, magnetic resonance imaging) and the activation of networks involved in the execution of specific tasks (fMRI), functional magnetic resonance imaging. In contrast to EEG/ERP, MRI/fMRI has excellent spatial resolution.

Myelin. Glial cells that cover the neuronal axons (oligodendrocytes in the central nervous system and Shwann cells in the peripheral nervous system) and speed the transmission of the nerve impulse down the axon.

Neural. Term that refers to components and events related to the nervous system (central and peripheral). Neuronal, on the other hand, refers only to neurons.

Oligodendrocytes. Glial cell type with few extensions. The functional of oligodendrocytes include wrapping around axons of the neurons of the central nervous system to produce the myelin sheath.

Phonological awareness. A meta-linguistic understanding that words are made up of speech sounds, including syllables and phonemes.

Polymorphism. Variation in the sequence of a given segment of DNA between individuals in a population.

Pyramidal neurons. A type of multipolar neuron located in various parts of the brain. In the prefrontal cortex they serve as primary sources of excitation.

Scaffolding. Term used in developmental psychology, pedagogy, and other social sciences to refer to the set of aids, guides, and information that a person (mainly children) receive to support skill development. These aids, which do not involve solving tasks for children, instead respond to children's current level of understanding and build from that to facilitate access to new learning and contribute to cognitive and emotional development.

Self-regulation. Psychological concept that refers to the ability to adjust, depending on context, one's thoughts, emotions, and behaviors aimed at goal-directed action. Self-regulation involves different processes of cognitive control (e.g., executive functions, meta-cognition) and emotions that can be studied at different levels of organization, from molecular to behavioral.

SES. Socioeconomic status (SES) is a measure of one's position or standing in society relative to others, often based on economic and social factors including one's income, occupation, and/or level of education. There are many methods of measuring SES, but any measure is generally considered a 'proxy variable' that stands the many factors that covary with SES (for further information, consult the following link:
https://www.crop.org/viewfile.aspx?id=238).

Striatum. Subcortical structure of gray matter that receives and sends information to different regions of the cerebral cortex. The striatum is associated with neural networks that involve the prefrontal cortex and, consequently, with cognitive and motor control processes.

Synapse. The physical gap or space between two neurons, in which the transmission of the nervous impulse is carried out (see Axon).

Theta. Neural oscillations in the frequency range of 3.5 and 7.5 Hz that are detected in the human brain through electroencephalography (see EEG). Theta activity is usually associated with the early stages of sleep and are generated by the interaction between the temporal and frontal lobes.

White and gray matter. White matter is the part of the central nervous system made up of myelin-coated axons that, macroscopically, have a whitish coloration; gray matter consists of the neuronal bodies without myelin and are therefore gray.

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Neuroscientific Perspectives on Poverty

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Over the last two decades, research in the field of poverty has begun to provide evidence that advances our understanding of how early adversity modulates brain development. When such evidence is used in the other disciplinary contexts, at times early brain development is claimed to predict adaptive behaviors and economic productivity during adult life, or such achievements are claimed to be impossible in some due to the supposed immutability of the long-term negative impacts of child poverty. Such statements have not only scientific but also political implications and therefor need to be examined in light of the available evidence. This is particularly important because such statements may lead to misconceptions and over-generalizations that in turn have the potential to affect investments in, as well the design, implementation, and evaluation of, programs targeting early childhood development. This book seeks to reduce such misconceptions and over-generalizations. The different chapters, written by prominent researchers in the cognitive neuroscientific study of poverty, provide evidence that leads to new hypotheses and reflections concerning the primary questions in the field of poverty studies from the neuroscientific perspective.