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The Neuroscience of Socioeconomic Inequality

Kimberly G. Noble¹, Melissa A. Giebler¹

¹Teachers College, Columbia University

Abstract

A burgeoning literature has recently begun investigating the links between socioeconomic inequality and the developing brain. This work suggests widespread disparities in both brain structure and function that begin as early as the first year of life. Here we review disparities in neural structure that have been reported in both cortical and subcortical gray matter, as well as in white matter. Disparities in brain function have also been reported, particularly in circuits that support language, memory, executive functioning, and emotion processing. We additionally review recent work investigating the mechanisms that underlie socioeconomic disparities in brain development. Taken together, this work has the potential to identify important targets for intervention in policy and practice.

In recent years, neuroscientists have begun tackling investigations of the neural bases of intricate educational, social, and political phenomena which had been previously considered the exclusive purview of social scientists. In particular, a burgeoning field has centered on the study of socioeconomic disparities in the developing human brain [1]. Childhood socioeconomic status (SES) - most commonly operationalized as some combination of parental educational attainment, occupational prestige, and family income - has for decades been linked with children's cognitive and socio-emotional development and academic achievement [1]. The neuroscience of SES represents a relatively recent complement to this work, yet progress has been rapid.

The first work using a neuroscience framework to investigate socioeconomic disparities in cognitive development employed behavioral assessments of cognitive systems such as language, memory, and executive function, which rely with some specificity on distinct neural circuits [1]. Socioeconomic disparities in these neurocognitive systems are evident as early as the second year of life [2] and persist throughout the lifespan [3]. Indeed, in one large-scale, decades-long longitudinal study, childhood SES was associated with later-in life language and executive functioning, independent of a genetic risk factor for cognitive impairment later in life [3].

Please address all correspondence to; Dr. Kimberly G. Noble, Columbia University, Teachers College, United States, kgn2106@tc.columbia.edu.

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A full overview of socioeconomic disparities in cognition and behavior is outside the scope of this review. Instead, here we review the recent literature directly linking socioeconomic inequality to children's brain structure and function. We additionally review recent work examining particular experiential mechanisms that may account for such links including the home language environment and family stress. We conclude with a consideration of how the neuroscience of SES may inform policy regarding social and economic supports for disadvantaged children.

SES and Brain Structure

Numerous studies have correlated socioeconomic inequality with brain structure, both in terms of cortical and subcortical gray matter, as well as white matter. Below we review each of these in turn.

SES and Cortical Gray Matter

Research has linked SES to cortical surface area, cortical thickness, and gray matter volume, most notably in frontal and temporal regions [4*,5*,6], which support the development of language, attention, executive function, emotion regulation, and memory [6,7**,8]. One cross-sectional study of 1,099 typically developing children and adolescents reported that family income and parental education were linked to cortical surface area, independently of genetic ancestry [6]. Income was logarithmically associated with surface area, such that small differences in income were associated with proportionately greater differences in surface area among the most disadvantaged children. These relationships were most prominent in perisylvian and prefrontal regions supporting language, reading, and executive functions. A longitudinal study of 623 children and adolescents also reported a positive association between SES and cortical surface area, in highly similar cortical regions [7**]. The strength of this association was stable between ages 5 and 25. Cortical surface area was also found to mediate the link between SES and reading ability [5*], executive functioning [6], and IQ [7**] in some of these studies.

Findings linking family SES to cortical thickness have been more variable, with some studies finding (generally positive) correlations [7**,9,10], but others reporting no links, despite adequate statistical power [6,11]. Interestingly, one study found no link between *family*-level socioeconomic characteristics and children's cortical thickness, but did find that greater *neighborhood* disadvantage was associated with greater longitudinal increases in cortical thickness across large swaths of temporal cortex bilaterally [11]. Neighborhood-level SES accounts for environmental factors and experiences that may be distinct from those of family-level SES, such as exposure to environmental toxicants and neighborhood violence, limited access to health care, or under-resourced schools, which may partially explain the differential effects on brain development [10,12,13,14]. In general, these apparent inconsistencies may also be due to the fact that SES links with cortical thickness may vary with age [15] or cognitive skill [16,17].

Cortical volume is the product of surface area and thickness, and is therefore a less precise measure than either of its constituents. Regardless, findings of studies employing cortical volume are generally consistent, particularly if we assume that results are likely driven by

differences in surface area. A very large study of 9498 children and teens found that socioeconomic disadvantage was associated with increased psychopathology and poorer neurocognitive performance, as well as reduced overall gray matter volume gray matter density [18]. A longitudinal study of 389 typically developing children and adolescents found that higher family income was associated with greater increases in frontal and temporal gray matter volume, with particularly steep gradients observed for children from poor or nearpoor homes [8]. Differences in regional gray matter volume accounted for up to 20% of the income-achievement gap in this sample [8]. Volumetric differences have also been reported very early in infancy [19], and early life poverty has been associated with reduced orbitofrontal volume 25 years later, and, subsequently, increases in conduct disorder, even when controlling for current socioeconomic factors and other demographic characteristics [20].

SES and Subcortical Gray Matter

Numerous studies have reported links between family socioeconomic characteristics - including parental education [4*,6,21,22] and family income [7**8,23] - and children's hippocampal volume, a structure which is critical for learning and memory [2,7**,8]. Socioeconomic disadvantage has been associated with slower longitudinal growth of the hippocampus [8], and such disparities in volume may increase with age [7**], though one study found that trajectories converged by late adolescence [23]. Other subcortical structures important for emotion and reward processing [7**,12,24], including the amygdala, thalamus, and striatum, have also been linked with socioeconomic disadvantage [7**,11,19], though results have been less consistent, and may vary by sex [25] or age [24].

SES and White Matter

Socioeconomic disparities have also been reported in white matter microstructure, particularly in tracts that support executive functions [26,27,28*], language [27,29], and reading [29,30]. Several small studies have linked higher parent education and/or family income with greater fractional anisotropy (FA; a measure of white matter integrity). This has been reported in the superior longitudinal fasciculus [28*,29,30], inferior longitudinal fasciculus [29,30], corticospinal tract [29,30], and cingulum [26,30]; disparities have also been linked to global network efficiency [27]. However, one large study of 1216 healthy young adults in Japan [31] found that only parent education, but not income, was weakly associated with FA, and only in small posterior clusters in the corpus callosum cerebellum.

Other findings have suggested that SES may moderate white matter-cognition relationships. One large study of 1082 children and teens reported that, in general, higher integrity of multiple tracts was associated with improved performance on an executive functioning task [26]. However, among children from lower SES homes, lower FA was associated with reduced performance, whereas children from higher SES homes showed preserved performance even in the face of low white matter FA. Similarly, a study of 129 children found that high FA in the inferior longitudinal fasciculus was associated with better reading performance. Again, among children with low FA in this region, children from lower SES homes struggled, whereas children from higher SES homes tended to do well, regardless of

FA [32], suggesting that socioeconomic advantage could potentially buffer against a neurobiological risk factor.

SES and Brain Function

In addition to studies describing socioeconomic disparities in brain *structure*, recent work has also investigated disparities in brain *function*. Specifically, socioeconomic factors have been associated with resting brain function, as measured by electroencephalography (EEG) and resting-state functional magnetic resonance imaging (rsfMRI), as well as with task-based measures of brain activation, including event-related potentials (ERP) and traditional fMRI.

SES and Resting Brain Function: EEG and Resting State fMRI Studies

One study of 66 full-term infants found that EEG power at birth was related to both language and memory outcomes at 15-months [33]. However, the authors found no associations between SES and EEG power at birth, suggesting that, although the variation of neonatal EEG power contained a meaningful signal, this signal was not explained by socioeconomic factors. A different study of 84 Italian infants suggested that by 6 months of age, higher SES is associated with greater high-frequency EEG power, which in turn is associated with subsequent language development [34]. Similarly, a longitudinal study of 65 typically developing infants who were scanned every 3 months during the first year of life found that, by 6 months of age, both family income and maternal education were marginally associated with functional connectivity in the default mode network and sensorimotor network [35]. One longitudinal study suggested that lower family income in preschool was associated with reduced connectivity between the hippocampus and amygdala and a number of cortical regions at school-age [36]. Further, a mediation analysis in this sample indicated that connectivity partially explained the relationship between lower family income and negative mood and depression at school-age. Finally, some work has suggested that functional brain development may be sensitive to neighborhood socioeconomic disadvantage, in addition to family-level socioeconomic disadvantage [12,37]. For example, in a large study of 1012 children and adolescents, youth living in more advantaged neighborhoods demonstrated a stronger positive association between age and functional connectivity compared to youth from more disadvantaged neighborhoods, in a pattern suggestive of faster functional brain development [13].

SES and Task-Based Brain Function - ERP and fMRI Studies

Recent work has begun investigating how socioeconomic factors relate to the neural bases of language, executive function and emotion processing, as measured online using ERP and fMRI.

Socioeconomic disparities in language development are well described, and several studies have begun exploring whether socioeconomic disparities may be observed in the neural processing of language. One study of 51 five-year-olds reported that inferior frontal gyrus lateralization during a rhyme-judgement task was related to maternal education, but not children's phonological skill [38], while two studies with small samples ($N = 32-36$) did not

find links between socioeconomic factors and neural activation during a phonetic discrimination [39] or story-listening task [40*]. A study of 64 children found socioeconomic differences in the neural response to learning new words [41]. While some evidence suggests that socioeconomic factors may interact with skill to predict neural activation [38,39], we caution against over-interpretation of interactions given small sample sizes, and urge that these questions be addressed in larger samples.

Several studies have also investigated socioeconomic disparities in the neural bases of executive functioning. One study of 215 twins found that neighborhood poverty, but not parental education or family income, was related to inferior frontal gyrus activation during a response inhibition (go/no-go) task [41], further supporting the idea that neighborhood disadvantage may account for additional variation in experience that is not captured by family-level SES. Other work focusing on disparities in working memory processing has revealed mixed results. One study reported that higher family income was associated with *greater* activation in a frontoparietal network during a WM task [28*], while another found that higher parental education was associated with *reduced* prefrontal recruitment during a similar task [42]. A third study reported that children from higher-income homes showed greater activation with higher WM loads, whereas children from lower-income homes exhibited greater activation at the lowest load [43]. Again, we encourage continued investigation of these questions in larger samples.

Finally, work has begun to examine socioeconomic disparities in the neural processing of emotions. One study of 207 adolescents reported that lower family income and lower subjective social status were associated with increased neural activation to angry facial expressions in the fusiform gyrus [44]. The same study reported that lower family income was associated with increased amygdala response to angry faces among youth without self-reported exposure to violence [44]. A study of mothers within 6 months postpartum reported that lower family income was associated with dampened amygdala responses to positive infant faces, but increased amygdala responses to negative infant faces [45]. Though nascent, this research suggests that economic disadvantage may lead to alterations in neural response to emotionally salient faces. Further research is needed to understand the pathways and mechanisms underlying this potential phenomenon.

Experience-Based Mechanisms

It has been questioned whether disparities in neurodevelopment and academic achievement are the product of social causation, in which SES-related differences in experiences and exposures lead to differences in outcomes, or whether outcome differences are the product of social selection, in which genetic underpinnings of academic achievement lead to differences in SES [46**]. Recent work in a large sample of nearly 5,000 children and teens investigated this question and concluded that both genetics, as measured by genome-wide polygenic scores (GPS), and SES, as measured by parental education and occupational status, independently predict academic achievement [47**]. Further, SES accounted for 60% more variance in academic achievement than did GPS [47**]. Moreover, in a longitudinal study of 142 children, family income predicted hippocampal volume, but this association

was not driven by genetic variance captured by polygenic scores of educational attainment, despite the fact that polygenic scores did predict income itself [21].

Thus, differences in experience are likely at least partially responsible for socioeconomic disparities in brain and behavior. If this is the case, it begs the question as to which experiences may account for these links, serving as potential targets for intervention? We consider two candidate mechanisms which have been proposed: (1) cognitive/linguistic stimulation in the home, and (2) family stress [48].

Several recent studies have found that adult-child conversational turns - i.e., contingent, responsive verbal interactions - mediate links between socioeconomic disparities and brain structure [5*,49] and function [40*] in language-supporting regions. Another study found that cognitive stimulation in the home, as reported by parents, indirectly mediated the link between SES and cortical thickness of the left middle frontal gyrus [28*]. Together, these studies suggest that cognitive and linguistic stimulation may play a key role in contributing to the emergence of socioeconomic disparities in the development of brain regions that contribute to higher-order language and cognitive skills.

Exposure to chronic stress has cascading effects on multiple brain and body systems, and has also been considered a likely mechanism linking socioeconomic disadvantage to neurodevelopmental differences [30]. To investigate this, Merz and colleagues measured chronic physiological stress in a sample of 94 socioeconomically diverse children, as indexed by hair cortisol concentration, which reflects the previous three months' average cortisol levels [4*]. The authors found that hair cortisol concentrations mediated associations between parental educational attainment and children's hippocampal volumes, driven by differences in CA3 and the dentate gyrus - subregions which, at a cellular level, have been shown to be particularly sensitive to the effects of chronic stress.

Conclusions

Though the neuroscience of SES has come a long way in a relatively short time, a good deal of work remains to be done. Investigations into the mechanisms linking socioeconomic disparities to neurodevelopmental outcomes hold real promise for identifying preventive and interventional targets. Additionally, better understanding of how the timing of socioeconomic disadvantage differentially impacts brain development will provide important insight into sensitive periods during which interventions are the most likely to be effective [48]. For example, early childhood is a sensitive period when the developing brain may be particularly vulnerable to experience. Socioeconomic disparities can emerge as early as the first year of life [19,34,35] and are evident through adolescence and into adulthood [1,48]. However, studies investigating how socioeconomic disparities in brain development *vary* across time are important for establishing additional periods of sensitivity. Results thus far from studies that address this question have yielded mixed results, with some studies reporting differential effects by age [7**,15,23,24] and others finding stable associations over time [6,7**,11,12,27,28*] Additional longitudinal research that traces socioeconomic disparities in brain development over time is necessary to resolve these inconsistencies and identify other periods of sensitivity [48].

As the field expands, it has the potential to inform the development of policy and practice [46**]. To do so successfully, however, interdisciplinary efforts between neuroscientists and social scientists will be critical. Further, it will be imperative to move past correlational studies to examine whether interventions *cause* changes in brain development, and in turn, mitigate against social and economic risks for low achievement. As an example, an interdisciplinary team of social scientists and neuroscientists is currently conducting the first randomized controlled trial of poverty reduction in early childhood, to assess whether a regular, monthly cash gift can change the trajectories of children from low-income homes for the better [50]. Such a study has the potential to leverage neuroscience findings to produce strong and clear evidence about the effect of income on early childhood development. This is one example of how, as a field, the neuroscience of inequality is poised to test questions that will provide direct evidence for social policies, and ultimately have a broader social impact on child and family well-being.

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Highlights

- Socioeconomic disparities in brain structure and function are prevalent.
- The mechanisms that may underlie disparities in brain development are discussed.
- Future steps and implications for the neuroscience of SES inequality are outlined.

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