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Socioeconomic disparities in academic achievement: A multi-modal investigation of neural mechanisms in children and adolescents

Maya L. Rosen [a,*], Margaret A. Sheridan [b], Kelly A. Sambrook [c], Andrew N. Meltzoff [a], Katie A. McLaughlin [a]

[a] Department of Psychology, University of Washington, United States
[b] Department of Psychology, University of North Carolina, Chapel Hill, United States
[c] Department of Radiology, University of Washington, United States

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ABSTRACT

Growing evidence suggests that childhood socioeconomic status (SES) influences neural development, which may contribute to the well-documented SES-related disparities in academic achievement. However, the particular aspects of SES that impact neural structure and function are not well understood. Here, we investigate associations of childhood SES and a potential mechanism—degree of cognitive stimulation in the home environment—with cortical structure, white matter microstructure, and neural function during a working memory (WM) task across development. Analyses included 53 youths (age 6–19 years). Higher SES as reflected in the income-to-needs ratio was associated with higher parent-reported achievement, WM performance, and cognitive stimulation in the home environment. Although SES was not significantly associated with cortical thickness, children raised in more cognitively stimulating environments had thicker cortex in the frontoparietal network and cognitive stimulation mediated the assocation between SES and cortical thickness in the frontoparietal network. Higher family SES was associated with white matter microstructure and neural activation in the frontoparietal network during a WM task, including greater fractional anisotropy (FA) in the right and left superior longitudinal fasciculi (SLF), and greater BOLD activation in multiple regions of the prefrontal cortex during WM encoding and maintenance. Greater FA and activation in these regions was associated higher parent-reported achievement. Together, cognitive stimulation, WM performance, FA in the SLF, and prefrontal activation during WM encoding and maintenance significantly mediated the association between SES and parent-reported achievement. These findings highlight potential neural, cognitive, and environmental mechanisms linking SES with academic achievement and suggest that enhancing cognitive stimulation in the home environment might be one effective strategy for reducing SES-related disparities in academic outcomes.

Introduction

Growing evidence indicates that brain development varies as a function of family socioeconomic status (SES; Brito and Noble, 2014; Noble et al., 2015; Ursache and Noble, 2016). These neural differences may play a role in the well-documented academic achievement gap between children raised in high-compared to low-SES households (Baydar et al., 1993; Brooks-Gunn and Duncan, 1997). SES-related differences in cognitive and brain outcomes are particularly pronounced in the domains of executive functions (EF) and language (Noble et al., 2005, 2007). EFs are a set of cognitive functions including inhibition, cognitive flexibility, and working memory (Miyake and Friedman, 2012). Here, we focus specifically on SES-related differences in working memory (WM), which involves the ability to hold in mind, manipulate, and update information in memory.

Children growing up in low-SES households exhibit worse WM than children raised in higher-SES families; these differences have been observed across the SES gradient and are not limited to children living in poverty (Hackman and Farah, 2009; Noble et al., 2005, 2007). EF abilities broadly, and WM specifically, are strongly associated with academic achievement (Best et al., 2011; Blair and Diamond, 2008; Finn et al., 2016). Understanding how the neural networks that support WM vary as a function of SES may shed light on neural pathways that explain the achievement gap. To that end, the present study uses a multi-modal

* Corresponding author. University of Washington, Box 351525, Seattle, WA 98195, United States.
E-mail address: rosenml@uw.edu (M.L. Rosen).

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approach to investigate SES-related differences in brain structure and function in neural systems involved in WM and the links between these neural systems and cognitive and academic performance in children.

Why might childhood SES influence brain development? It is likely that many aspects of SES produce differences in neural structure and function, and ultimately academic achievement, including cognitive and social stimulation, environmental predictability, parenting, exposure to toxins, nutrition, and exposure to violence (Johnson et al., 2016). Here, we focus on whether SES-related differences in neural structure and function are driven by differences in the degree of cognitive stimulation in the home environment–a modifiable factor that could be targeted with early intervention.

Children raised in low-SES families, on average, experience lower levels of cognitive stimulation, interaction with adults, linguistic complexity, and access to enriching experiences at home and school than children raised in high-SES families (Hart and Risley, 1995; Bradley et al., 2001; Bradley and Corwyn, 2002; Hackman et al., 2015). This reduction in cognitive and social stimulation is argued to constrain early forms of learning that rely on rich sensory, linguistic, and social input, resulting in accelerated synaptic pruning throughout the cortex (McLaughlin et al., 2017; McLaughlin and Sheridan, 2016; Sheridan and McLaughlin, 2016). These patterns could produce age-specific reductions in cortical thickness and surface area among children from low-SES backgrounds.

Existing research on SES and neural structure is consistent with these predictions (Jednoróg et al., 2012; Lawson et al., 2013; Mackey et al., 2015; Noble et al., 2012, 2015; Piccolo et al., 2016). Lower parental education and family income are associated with reduced cortical thickness and surface area throughout the cortex (Mackey et al., 2015; Noble et al., 2015), with the strongest association between SES and cortical surface area at the lowest levels of income (Noble et al., 2015). SES-related differences are particularly pronounced in regions underlying WM and language, including dorsolateral prefrontal cortex (dlPFC), superior temporal cortex, and superior parietal cortex (Noble et al., 2012, 2015). Cortical thickness in dlPFC and superior temporal cortex decreases more rapidly in children from low-SES backgrounds followed by an attenuation of this thinning in adolescence (Piccolo et al., 2016), consistent with the idea that children in low-SES environments exhibit accelerated pruning of synaptic connections early in life that produces more rapid declines in cortical thickness and surface area across childhood (McLaughlin et al., 2014, 2017; Sheridan & McLaughlin, 2014, 2016). Although accumulating evidence demonstrates reductions in cortical thickness and surface area among children raised in low-SES environments, we are unaware of prior research directly examining the hypothesis that these differences are driven by the reductions in cognitive stimulation experienced by low-SES children. We provide the first empirical test of this hypothesis in the current paper.

Differences in cortical structure may have implications for cognitive and academic outcomes. Longitudinal data indicate that accelerated cortical thinning in childhood followed by attenuated thinning in adolescence—a pattern observed among low-SES children (Piccolo et al., 2016) is associated with lower cognitive ability (Shaw et al., 2006). Similarly, greater thickness in temporal, parietal, and occipital cortex is associated with better standardized test scores in adolescents (Mackey et al., 2015). Thus, reductions in cortical thickness may be a mechanism linking low-SES with poor academic outcomes.

Although SES-related differences in cortical structure are well documented, few studies have examined the associations of SES with white matter microstructure, particularly in children. White matter microstructure in fronto-striatal and fronto-temporal tracts is reduced in children who have experienced adverse environments characterized by deprivation in cognitive and social stimulation, such as institutional rearing and neglect (Eluvathingal et al., 2006; Kumar et al., 2014; Hanson et al., 2013; Bick et al., 2015). Because children raised in low-SES families also are likely to experience lower levels of cognitive stimulation than children raised in high-SES families (Bradley and Corwyn, 2002), it is possible that SES may have similar influences on white matter microstructure, although this is largely untested. Evidence from adults is somewhat consistent with this hypothesis: global white matter integrity follows an SES gradient in adults, such that greater education, income, and community-level SES are associated with higher fractional anisotropy (FA) across the entire brain (Gianaros et al., 2013). Variability in white matter structure, in turn, influences cognitive outcomes. In particular, greater integrity of the superior longitudinal fasiculus (SLF), a tract that connects the lateral PFC to the parietal cortex, has been linked to better WM (Mabbott et al., 2009; Vestergaard et al., 2011) and higher educational attainment in adolescents (Noble et al., 2013), suggesting that this tract may play an important role in SES-related variation in WM and academic achievement.

Few studies have examined SES-related differences in neural function during WM tasks in children, although such differences in neural function have been observed in relation to language processing (e.g. Raizada et al., 2008), emotion regulation (e.g. Kim et al., 2013), and academic subjects including mathematics and reading (e.g. Demir-Lira et al., 2016; and Noble et al., 2006). Existing evidence suggests that SES is associated with PFC function during multiple forms of EF. During novel rule-learning, low-SES children perform more poorly and exhibit a more diffuse pattern of PFC activation than higher-SES children (Sheridan et al., 2012). Additionally, SES is related to reduced inhibitory control in adolescents and greater recruitment of the dorsal anterior cingulate cortex, coupled with reduced connectivity between the dorsal anterior cingulate and dorsolateral PFC specifically among low SES girls (Spielberg et al., 2015). During a WM task, children from lower-income backgrounds exhibit reduced PFC and superior parietal recruitment than children from higher-SES families (Finn et al., 2016). In that study, WM capacity and fronto-parietal recruitment mediated the association between SES and performance on a statewide mathematics exam. These findings suggest that differences in neural recruitment in the frontoparietal network observed among low-SES children may contribute directly to academic performance.

In the present study we used a multi-modal neuroimaging approach to investigate the associations of parental SES with brain structure and function, including cortical structure, white matter microstructure, and neural function during a WM task. We focused on SES-related differences in the frontoparietal network because of its known role in WM (Corbetta and Shulman, 2002; Curtis & D'Esposito, 2003), which was the focus of our behavioral and fMRI task. Moreover, previous studies have found SES-related differences in neural structure and function in the frontoparietal network (Sheridan et al., 2012; Noble et al., 2013; Finn et al., 2016). For structural region of interest (ROI) analyses, we focused on the middle frontal gyrus (MFG) and superior parietal lobule/intraparietal sulcus (SPL/IPS), key frontoparietal regions that are recruited during WM tasks (Corbetta and Shulman, 2002). For white matter analyses, we examined the superior longitudinal fasciculus (SLF) because it connects the prefrontal and parietal cortices and is associated with WM performance (Mabbott et al., 2009; Vestergaard et al., 2011). In our fMRI approach, we used a conservative whole brain approach to examine SES-related differences in neural recruitment, which demonstrated clear differences in our frontoparietal regions. We then extracted ROIs from frontoparietal regions to examine associations with task performance and academic achievement.

We hypothesized that SES would be associated with frontoparietal structure and function, including positive associations with cortical thickness in the MFG and SPL/IPS; positive associations with white matter integrity in the SLF; and positive associations with BOLD signal in the prefrontal and parietal cortex during a WM task. We expected that cortical thickness, white matter microstructure, and BOLD signal in these frontparietal regions would be associated not only with SES, but also with parent-reported academic achievement. Importantly, we also predicted that SES-related differences in neural structure and function would be driven by differences in the degree of cognitive stimulation in the home environment. Together, we expected that WM performance, cognitive stimulation, and neural structure and function would be mechanisms