Cerebral Cortex, 2022, 1–16

https://doi.org/10.1093/cercor/bhac120

Original Article

Associations between neighborhood socioeconomic status, parental education, and executive system activation in youth

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Abstract

Socioeconomic status (SES) can impact cognitive performance, including working memory (WM). As executive systems that support WM undergo functional neurodevelopment during adolescence, environmental stressors at both individual and community levels may influence cognitive outcomes. Here, we sought to examine how SES at the neighborhood and family level impacts task-related activation of the executive system during adolescence and determine whether this effect mediates the relationship between SES and WM performance. To address these questions, we studied 1,150 youths (age 8–23) that completed a fractal *n*-back WM task during functional magnetic resonance imaging at 3T as part of the Philadelphia Neurodevelopmental Cohort. We found that both higher neighborhood SES and parental education were associated with greater activation of the executive system to WM load, including the bilateral dorsolateral prefrontal cortex, posterior parietal cortex, and precuneus. The association of neighborhood SES remained significant when controlling for task performance, or related factors like exposure to traumatic events. Furthermore, high-dimensional multivariate mediation analysis identified distinct patterns of brain activity within the executive system that significantly mediated the relationship between measures of SES and task performance. These findings underscore the importance of multilevel environmental factors in shaping executive system function and WM in youth.

Key words: adversity; development; executive function; fMRI; working memory.

Introduction

Socioeconomic status (SES) is a multifaceted construct measuring the social standing or access to resources of an individual or group, and often includes factors like income, education, and neighborhood environment. Low SES has been related to differences in diverse measures of brain development and cognition in youth (Bradley and Corwyn 2002; Pollak and Wolfe 2020). In particular, working memory (WM), a component of executive function, has been consistently shown to vary by SES, with low-SES individuals having poorer performance (Noble et al. 2007; Hackman et al. 2015; Leonard et al. 2015). The impact of SES on WM may be particularly important during youth, when WM improves dramatically (Gur et al. 2012, 2014; Satterthwaite et al. 2013; Ullman et al. 2014; Luna et al. 2015; Simmonds et al. 2017). Indeed, prior work suggests that differences in WM may in part explain SES-related differences in academic performance (Gathercole et al. 2004; Best et al. 2011). However, the neurobiological mechanisms that link low SES to WM differences in youth remain incompletely described (Hart et al. 2007; Sheridan and McLaughlin 2014; Rosen et al. 2019).

Studies have provided evidence that WM performance is subserved by a spatially distributed set of brain regions within the executive system, including the dorsolateral prefrontal cortex (DLPFC), anterior insula, intraparietal sulcus, precuneus, and cerebellum (Satterthwaite et al. 2013; Samartsidis et al. 2019; Rosenberg et al. 2020). During WM tasks, activation of this distributed executive system has been shown to be reduced in youth with low family income (Finn et al. 2017), while lower parental education has also been associated with inefficient recruitment of elements of the executive system (Sheridan et al. 2017). Additionally, higher levels of early life stress, including measures of

Received: August 12, 2021. **Revised:** February 16, 2022. **Accepted:** February 17, 2022

financial strain and housing challenges, predict greater resting-state homogeneity in the left middle frontal gyrus, which in turn is associated with lower levels of cognitive control (Demir-Lira et al. 2016). These results from functional magnetic resonance imaging (fMRI) cohere with findings from studies using structural MRI, which have reported that low-SES youth have reduced cortical surface area in executive regions (Noble et al. 2015; Leonard et al. 2019).

Notably, most studies examining the neural underpinnings of the relationship between SES and cognitive function have operationalized SES using individual-specific variables, such as family income or parental education. However, accruing evidence suggests that neighborhood-level factors can impact cognition above and beyond individual-specific measures (Brito and Noble 2014; Tomlinson et al. 2020). Specifically, recent work has begun to utilize measures of environmental adversity at the neighborhood level, which include crime rates, social capital, or access to housing (Leventhal and Brooks-Gunn 2000). These factors have been shown to impact both physical (Boylan and Robert 2017) and mental health outcomes (Aneshensel and Sucoff 1996), through proposed mechanisms such as environmental toxins or allostatic load, both of which are found at higher levels in low-income neighborhoods (Gustafsson et al. 2014; Liu and Lewis 2014; Robinette et al. 2016).

Studies have shown that cognitively enriched care within the home supports neurocognitive development in young children (Farah et al. 2021; Lurie et al. 2021) aligning with work in animal models, which suggest that an enriched environment may support cognitive performance (Yuan et al. 2012). Such enriched environments have been linked to various neurocognitive measures including brain size and cortical thickness (Kolb et al. 2012). Children in low-SES neighborhoods are more likely to attend disadvantaged schools or have less access to cognitively enriching experiences, like a trip to a museum or a library (Entwisle et al. 1994; Bradley and Corwyn 2002; Evans 2004). Given these considerations, it is possible that cognitive stimulation and exposure to novel experiences at the neighborhood level support cognitive function in the same capacity.

Work using large-scale neuroimaging studies has found environmental adversity measured on the neighborhood scale is associated with neurocognitive performance across a variety of domains of executive function, including WM (Gur et al. 2019; Vargas et al. 2020). Neighborhood disadvantage has also been related to other neuroimaging parameters, including lower gray matter volume (Butler et al. 2018), blood-oxygen level dependent (BOLD) activation in response to social exclusion (Gonzalez et al. 2015), development of functional networks (Tooley et al. 2019), as well as structural differences including lower surface area in the prefrontal cortex (Vargas et al. 2020) and lower volume in the dorsolateral prefrontal cortex and right hippocampus (Taylor et al. 2020).

These studies suggest that understanding the relationship between SES, cognition, and brain function requires consideration of adversity measured at the community level. However, relatively few studies have examined the relationship of different measures of SES and neurocognitive outcomes. Notably, Rakesh et al. (2021) found that SES measured at the family level and at the neighborhood level had distinct associations with resting-state functional connectivity in both the sensorimotor and frontoparietal networks. Furthermore, neighborhood disadvantage and parental support may interact in specific ways, with education-oriented parental practices being more helpful for children living in low-SES neighborhoods (Catsambis and Beveridge 2001; Greenman et al. 2011). Additionally, positive parenting, as measured by coded verbal and non-verbal interactions during a problem solving task, has been found to moderate the effect of neighborhood disadvantage on brain development (Whittle et al. 2017).

In the current study, we investigated how family-level and neighborhood-level indicators of SES relate to WM and brain function during youth. Specifically, we used geocoded block-level data and reported parental education to investigate the association between different metrics of SES and executive system activation during a WM fMRI task. We hypothesized that both lower neighborhood SES and parental education would be associated with reduced activation of the executive system, with neighborhood SES accounting for a broader effect. Additionally, we hypothesized that multivariate patterns of brain activation within the executive system would mediate the relationship between measures of SES and performance on an in-scanner WM task.

Materials and methods

Participants

We examined a cross-sectional sample of 1,536 participants from the Philadelphia Neurodevelopmental Cohort (PNC) (Satterthwaite et al. 2016) who underwent functional neuroimaging while completing a fractal n-back task (mean age = 14.9, range 8–23, 837 = female). Data were collected from November 2009, through December 2011. Of these individuals, 378 were excluded for medical comorbidities that impact brain function ($n = 148$), image quality ($n = 227$), or incomplete clinical data ($n = 11$). The final sample included in the analysis consisted of 1,150 individuals (mean age = 15.4, range 8–23; 622 = female). A socio-demographic description of the sample is included in Table 1.

Measure of neighborhood socioeconomic status

The quantification of neighborhood SES in this sample has been detailed previously (Moore et al. 2016). A set of geocoded variables were obtained from participant addresses and incorporated 2010 census data from the greater Philadelphia area. Examples of characteristics in this census-block level data included median family

Table 1. Sociodemographic characteristics of the sample.

	N	Percent
Sex		
Male	534	46.43%
Female	616	53.57%
Race		
White	554	48.17%
Black/African American	457	39.74%
US Indian/Alaska Native	4	0.35%
Asian	12	1.04%
More than 1 race	123	10.70%
Ethnicity		
Hispanic	80	6.96%
Not Hispanic	1,070	93.04%

income, percent of residents who are married, percent of homes which are family homes, and percent of people in poverty. Census block groups typically contain 600–3,000 persons and can also vary in square footage, meaning they can vary (sometimes extremely) in density. A weighted factor score of neighborhood level SES was generated from these variables using the Thurstone Method (Thurstone 1935). The 2-factor solution in Table 1 of Moore et al. (2016) includes 1 factor capturing SES-related variables (e.g. median family income) and a second factor capturing household characteristics "typical" of that area (e.g. percent with children, percent English speakers). Here, we used Factor 1 as our neighborhood measure of SES. As Factor 2 was related to the characteristics of households (largely reflecting immigration status independent of SES), which was not the focus of the current study, it was not analyzed here. The composite score for the neighborhood SES factor (mean = −0.15, sd = 1.02) was a weighted combination of the following variables: percent of residents who are married, median family income, percent of residents with at least a high school diploma, percent of residents employed, median age, percent of residents that are female, percent of real estate that is vacant, population density, and percent of residents in poverty.

To measure family level SES, we used the mean of maternal and paternal education, or, if only 1 measure was available, whichever measure was reported (mean parental education = 14.13, sd = 2.33). Measures of family and neighborhood SES were significantly correlated with each other ($r = 0.55$, $P < 0.001$).

Task design

The fractal *n*-back task used in the PNC has previously been described in detail (Satterthwaite et al. 2012; Shanmugan et al. 2016). Briefly, participants completed a fractal *n*-back WM task (Ragland et al. 2002) during fMRI as a measure of WM (Fig. 1A). The task was structured with a block-design using 3 conditions of increasing WM load: 0-back, 1-back, and 2-back. In the 0-back condition, participants responded to a single target image. In the 1-back condition, participants responded if the image presented was the same as the previous image. In the 2-back condition, participants responded if the image presented was the same as the image presented 2 trials previously. Each condition included 20 trials over 60s, and was repeated over 3 blocks. Participants were cued with verbal instructions as to which condition they would be completing at the beginning of each block.

Image acquisition

Participants completed a neuroimaging protocol that included fMRI, T1, and B0 sequences, collected at a single scanner (Siemens 3-T, 32-channel head coil). A magnetization-prepared rapid acquisition gradient echo T1-weighted image was acquired to aid spatial normalization to standard atlas space, using the following parameters: TR, 1,810 ms; TE, 3.51 ms; TI, 1,100 ms; FOV, 180 × 240 mm; matrix, 192 × 256; 160 slices; slice thickness/gap, 1/0 mm; flip angle, 9°; effective voxel resolution, 0.9 × 0.9 × 1 mm. Blood oxygen level-dependent fMRI was acquired using a whole-brain, single-shot, multislice, gradient-echo echo-planar sequence with the following parameters: 231 volumes; TR, 3,000; TE, 32 ms; flip angle, 90°; FOV, 192 × 192 mm; matrix 64 × 64; 46 slices; slice thickness/gap 3/0 mm; effective voxel resolution, 3.0 × 3.0 × 3.0 mm. Additionally, a B0 field map was acquired for application of distortion correction procedures, using the following double-echo gradient recall echo sequence: TR, 1,000 ms; TE1, 2.69 ms; TE2, 5.27 ms; 44 slices; slice thickness/gap, 4/0 mm; FOV, 240 mm; effective voxel resolution, 3.8 × 3.8 × 4 mm.

Image processing

Image preprocessing is described in detail in our prior work describing this dataset (Satterthwaite et al. 2014; Shanmugan et al. 2016). Briefly, basic preprocessing of *n*-back task images used tools from FSL, including slice time correction, skull stripping, motion correction, spatial smoothing, and grand mean scaling. Time-series analysis of subject-level imaging data modeled the *n*-back task's 3 condition blocks (0-back, 1-back, and 2-back) using FEAT. Subject-level statistical maps of the primary 2-back > 0-back contrast were distortion corrected, coregistered to the MNI 152 1-mm template registered T1 image, and normalized using Advanced Normalization Tools (Avants et al. 2008). Images were downsampled to 2 mm resolution before group-level analysis. All transforms were concatenated so that only a single interpolation was performed.

Behavioral analysis

We summarized performance during the *n*-back task using the signal detection measure *d*'.

$$(d' = z(F) - z(H))$$

where F and H are the false alarm and hit rates during the task.

This measure incorporates both correct responses and false positives in order to limit the impact of response bias on the measure of accuracy (Snodgrass and Corwin 1988).

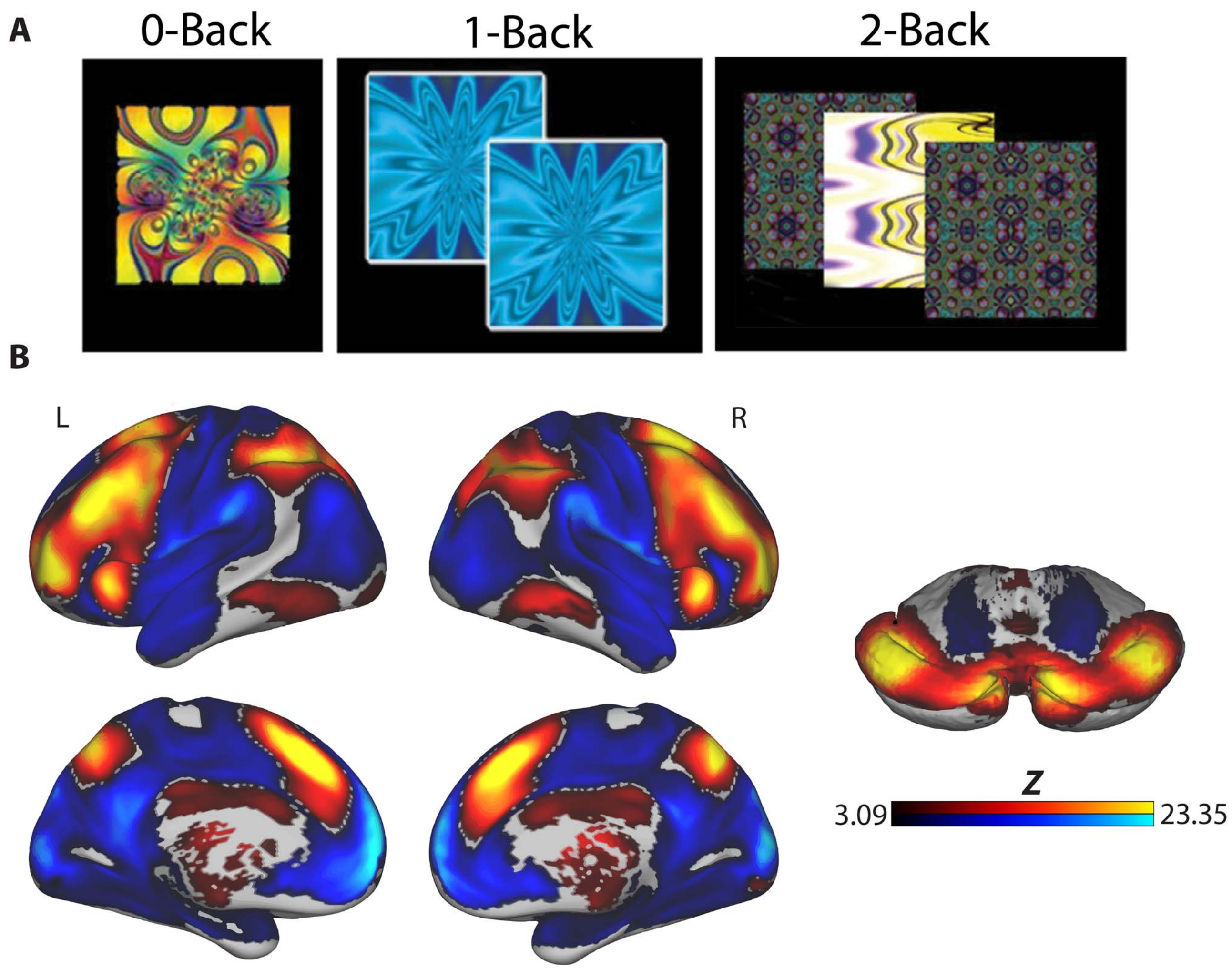

Fig. 1. The effect of WM load on brain activation. (A) WM was measured using a fractal version of the *n*-back WM task. (B) Increased WM load, operationalized by the 2-back > 0-back contrast, robustly activated the distributed executive system, while deactivating nonexecutive regions (image was thresholded at $z > 3.09$, cluster corrected at $P < 0.05$).

Group-level analysis

Our primary group-level analysis sought to characterize the association between neighborhood SES, parental education, and changes in brain activation under WM load (2-back > 0-back). We conducted mass-univariate voxelwise analyses using tools from FSL (Jenkinson et al. 2012), where activation in the 2-back vs. 0-back condition was the outcome, and neighborhood SES and parental education were the predictors of interest; age, sex, and in-scanner motion were included as covariates. We controlled for multiple comparisons using cluster correction as implemented in AFNI with 3dFWMHx and 3dClustSim (voxel height $z > 3.09$, cluster probability $P < 0.05$). Visualizations were generated using Connectome Workbench, developed under the auspices of the Human Connectome Project at Washington University in St. Louis and associated consortium institutions (http://www.humanconnectome.org) (Marcus et al. 2011).

Sensitivity analyses

To evaluate the potentially confounding influence of other participant factors, we conducted sensitivity analyses that included additional model covariates. Specifically, we repeated the mass-univariate analysis described above, but also included exposure to traumatic stress, and task performance (d') as model covariates. Traumatic stress was assessed as part of a structured clinical interview (GOASSESS), and quantified by the lifetime number of categories of exposure to traumatic stressful events experienced by a participant (range 0–8) (Calkins et al. 2015; Barzilay et al. 2019).

Analysis of age by SES interaction

To examine the interaction of age and SES on activation during WM, we repeated the mass-univariate analysis described above in 2 models, including interaction terms for age and neighborhood SES, and age and parental education respectively.

Mediation analyses

As a final step, we sought to understand how multivariate patterns of brain activation might mediate the observed association between both measures of SES and WM performance. To do this, we examined principal directions of mediation (Chén et al. 2018; Geuter et al. 2020) using the M3 Mediation toolbox from the Cognitive

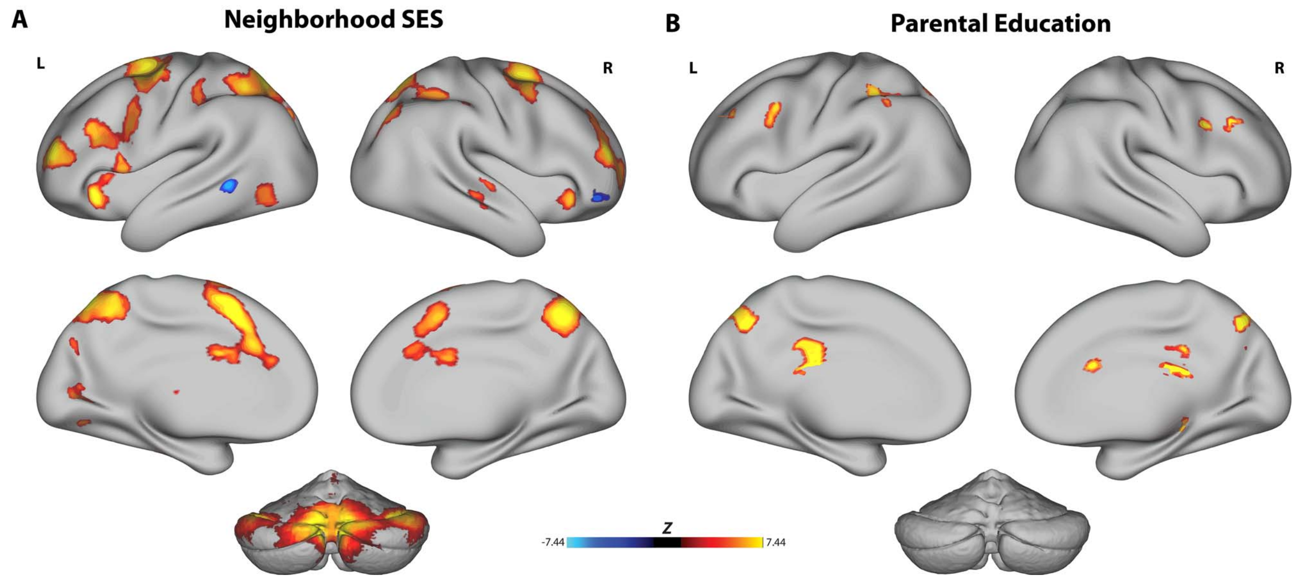

Fig. 2. Both higher neighborhood SES and higher parental education were significantly associated with greater activation throughout the executive system. (A) A mass univariate analysis revealed higher neighborhood SES was related to increased activation in the bilateral dorsolateral prefrontal cortex, ventromedial prefrontal cortex, right and left frontal poles, superior parietal cortex, precuneus, as well as the bilateral cerebellar crus I & II. (B) Higher parental education was associated with increased activation in the precuneus cortex, primary motor cortex, right hippocampus, and bilateral dorsolateral prefrontal cortex.

and Affective Neuroscience Lab (CANlab; available at https://github.com/canlab/MediationToolbox). This type of mediation analysis is guided by principal component analysis, and seeks to extract linear combinations of high-dimensional neuroimaging data that maximize the indirect effect (i.e. the mediation) between independent and dependent variables. The result is a set of orthogonal principal directions of mediation (PDMs) that can be mapped back to the original neuroimaging data space to provide interpretable mediation effects between X and Y variables (see Chén et al. 2018 for details).

To avoid overfitting and test the generalizability of the PDMs observed in our data, we first divided our sample into training ($n = 576$) and testing ($n = 574$) sets that were matched on neighborhood SES. This enabled us to model PDMs in the training set and then apply the model to the unseen data in our test set. We tested 2 separate mediation models, evaluating both neighborhood SES and parental education as dependent variables. In order to ensure that the PDM's were generated controlling for the other measure, we regressed the effects of each measure out of the other. First, we conducted an initial principal component analysis in R, which resulted in 10 principal components explaining more than 1% of variance in the data. We then used singular value decomposition to reduce the dimensionality of the neuroimaging data from the training subset. This resulted in a 576 (participants) x 10 (principal components) matrix, which was used to estimate the PDM's. Next, we tested significance of the indirect path between each measure of SES and WM performance associated with each PDM, which was determined using a bootstrap procedure with 10,000,000 iterations, controlling for age, sex, and motion as nuisance covariates.

To validate the estimated PDM's, we applied the model generated on the training data to the unseen test data and performed the same bootstrapping procedure to assess significance of indirect path coefficients while controlling for the same set of nuisance covariates. Thus, the mediation effect encoded by each PDM was tested for significance twice; once in the training data and again on unseen test data. Next, in order to better interpret the mediation effects, we extracted the weights at each voxel from the PDM's that yielded significant indirect paths on both the training and the testing data. The contribution of each voxel to the PDM was assessed for significance using bootstrap analyses, while controlling for type I error with cluster correction as stated above (voxel height $z > 3.09$, cluster probability $P < 0.05$). This resulted in a matrix of P-values which could be interpreted as a 3D image.

Results

Lower socioeconomic status is associated with attenuated activation of the executive system

As previously reported (Satterthwaite et al. 2013), the n-back task robustly activated the distributed components of the brain's executive system (Fig. 1B) and deactivated nonexecutive regions, including the default mode network. We hypothesized that higher neighborhood and family SES would be associated with greater recruitment of the executive system. Mass univariate voxel-wise analysis revealed that higher neighborhood SES was associated with greater bold activation in 16 clusters within the executive system, and greater deactivation in 2 clusters in the default mode network (see Fig. 2A and Table 2A). These regions included bilateral dorsolateral prefrontal

Table 2. Main model including neighborhood SES and parental education.

Cluster region	Voxels	Max (z)	Peak X (mm)	Peak Y (mm)	Peak Z (mm)
A. Neighborhood SES					
Superior frontal gyrus, middle frontal gyrus	4,553	11.6	30	4	66
Lateral occipital cortex, precuneus cortex	4,060	12.69	12	76	58
Right frontal pole	1,050	8.28	−40	−50	22
Left frontal pole	946	9.42	36	−54	24
Cerebellum	457	9.11	4	78	−30
Cerebellum	436	8.36	−42	66	30
Cerebellum	280	7.9	36	40	−38
Frontal orbital cortex	269	8.94	30	−28	−4
Lingual gyrus	205	5.65	12	70	2
Lateral occipital cortex	179	6.5	46	68	−12
Postcentral gyrus	158	6.11	48	32	46
Inferior frontal gyrus	144	6.45	46	−12	6
Middle temporal gyrus	139	−5.51	66	50	−4
Superior temporal gyrus	134	4.91	−68	18	−10
Frontal orbital cortex	114	7.17	−32	−28	−4
Left thalamus	108	6.05	16	30	12
Supramarginal gyrus	94	5.3	−48	30	46
Right frontal pole	91	−5.27	−42	−52	−8
B. Parental education					
Precuneus cortex, lateral occipital cortex	472	9.37	10	−76	−56
Supramarginal gyrus	215	6.98	28	46	40
Right precentral gyrus	189	5.47	−42	−2	32
Cingulate gyrus	175	5.17	0	34	20
Left precentral gyrus	169	6.23	40	−4	36
Cingulate gyrus	129	6.47	−10	−20	24
Left middle frontal gyrus	108	6.84	3	−20	24
Right hippocampus	107	5.54	−28	36	4
Angular gyrus	92	6.51	−40	50	36
Right middle frontal gyrus	89	5.99	−38	−24	30

cortex (DLPFC), anterior insula, paracingulate, frontal pole, and the supplementary motor area, regions of the parietal cortex and cerebellum, including bilateral superior parietal cortex, precuneus, bilateral cerebellar crus I & II, as well as parts of the inferior temporal cortex and temporal pole. Higher parental education was associated with increased activation in 10 clusters in the executive system (see Fig. 2B and Table 2B). These clusters were located in spatially distinct parts of the bilateral dorsolateral prefrontal cortex, cingulate cortex, and parietal cortex. Furthermore, several regions showed significant associations with both measures of SES, including the parietal cortex and precuneus, as well as parts of the dorsolateral prefrontal cortex (see Fig. 3).

Next, to better understand what was driving the 2b > 0b effect, we conducted post-hoc analyses examining the effect of 0-back and 2-back conditions separately. For both parental education and neighborhood SES, there was a significant relationship between the average BOLD signal across activation related to each measure in the 2-back condition, but not in the 0-back condition, suggesting that the main effect was driven primarily by the 2-back condition (Fig. 4).

Sensitivity analyses

A separate mass univariate voxelwise analysis that controlled for additional covariates including in-scanner task performance (as measured by *d'*) and exposure to traumatic events, revealed a highly convergent pattern of results for neighborhood SES (Table 3), while activation related to parental education did not survive correction for multiple comparisons.

Effect of neighborhood SES varies by age

We observed a significant age by neighborhood SES interaction in a cluster that was located on the border between the task-negative posterior cingulate and task-positive precuneus (Supplementary Fig. S1A). The interaction was such that older participants demonstrated more task deactivation in this region as neighborhood SES increased, and younger participants demonstrated more task activation as neighborhood SES increased (Supplementary Fig. S1B). There was no significant interaction between age and parental education.

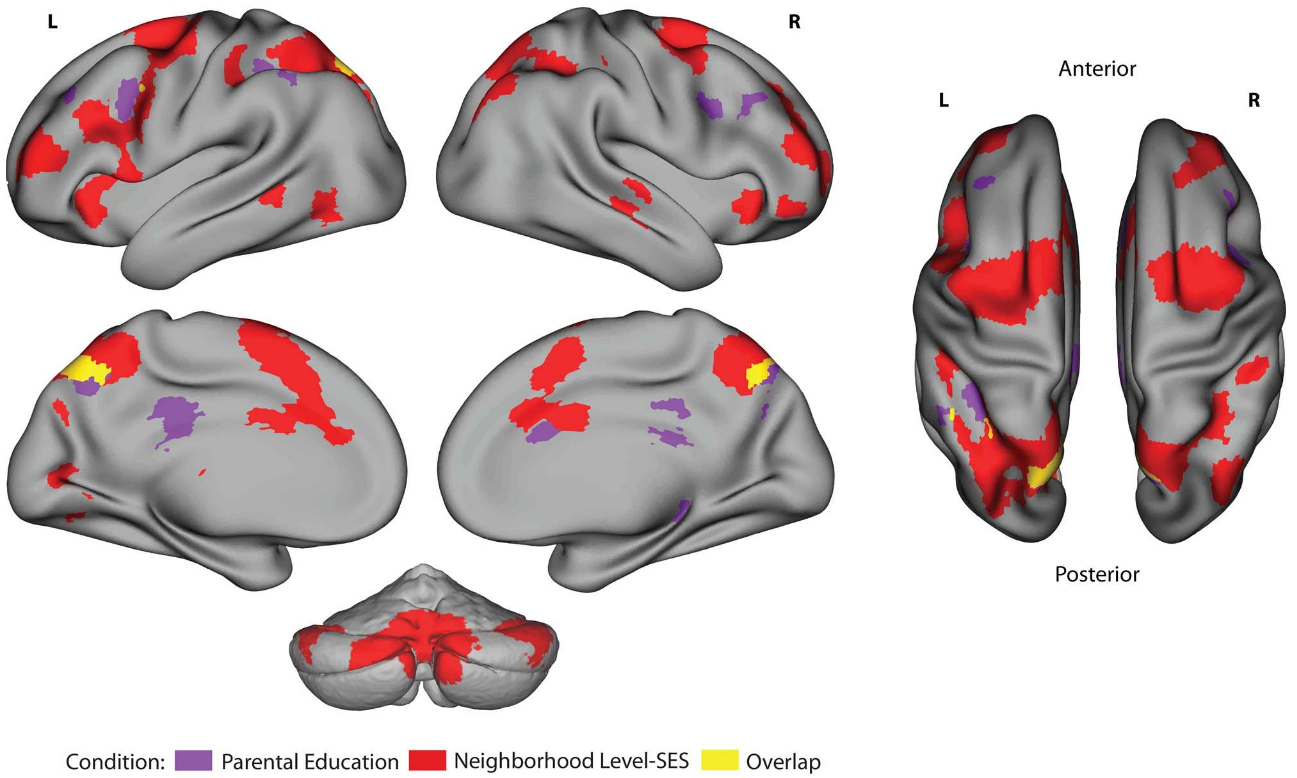

Fig. 3. Higher neighborhood and parental education were each associated with distinct patterns of increased activation. There were also some regions of overlapping associations, including parts of the parietal and dorsolateral prefrontal cortices.

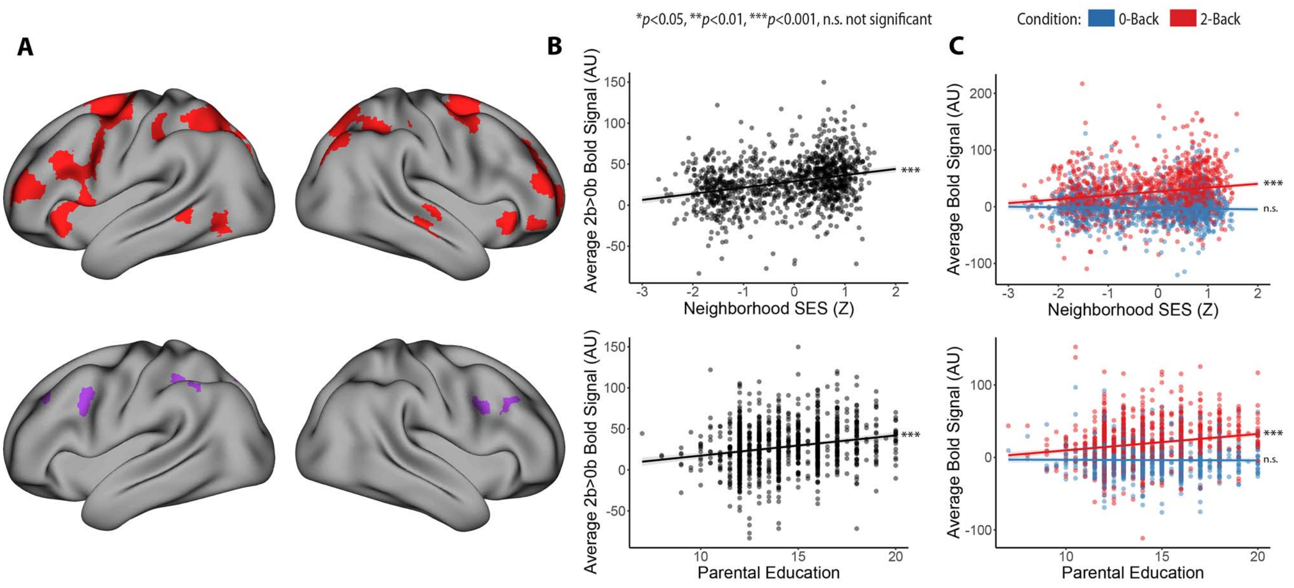

Fig. 4. The effect of neighborhood SES on executive system activation was driven by individual differences in activation during the high WM load condition (2-back). Significant clusters were observed within the executive system for both (A) neighborhood SES (top) and parental education (bottom). The average effect in all significant clusters is presented in (B). To understand what was driving the main contrast, each condition was modeled separately in post-hoc analyses. (C) Post-hoc mixed effect models of the effect of each measure on activation during the 2-back and 0-back conditions each revealed significant relationships between SES and 2-back activation ($P < 0.0001$). In contrast, neither indicator of SES was significantly associated with activation during the 0-back condition.

Multivariate patterns of activation mediate the relationship between measures of socioeconomic status and working memory performance

Given the observed association between both measures of SES and executive activation, the significant association between measures of SES and task performance (Fig. 5), and the known relationship between neural activation and WM performance (Shamosh et al. 2008; Satterthwaite et al. 2013), we investigated whether multivariate patterns of brain activation mediated the relationship between parental education or neighborhood SES and task performance.

Table 3. Sensitivity analysis including traumatic stress exposure and task performance as additional covariates.

Cluster region	Voxels	Max (z)	Peak X (mm)	Peak Y (mm)	Peak Z (mm)
Lateral occipital cortex, precuneus cortex, superior parietal cortex	1,282	7.09	−12	68	64
Left superior frontal gyrus, precentral gyrus	1,022	6.55	30	6	66
Right precentral gyrus, middle frontal gyrus, superior frontal gyrus	627	5.98	−30	−2	68
Left frontal pole	364	5.27	39	−54	24
Right frontal pole	159	5.36	−42	−52	26
Left post central gyrus	141	4.5	48	30	38
Left middle temporal gyrus	134	−5.2	52	50	−4
Right superior temporal gyrus	101	5.23	−66	22	0
Right postcentral gyrus	96	4.72	−50	30	42

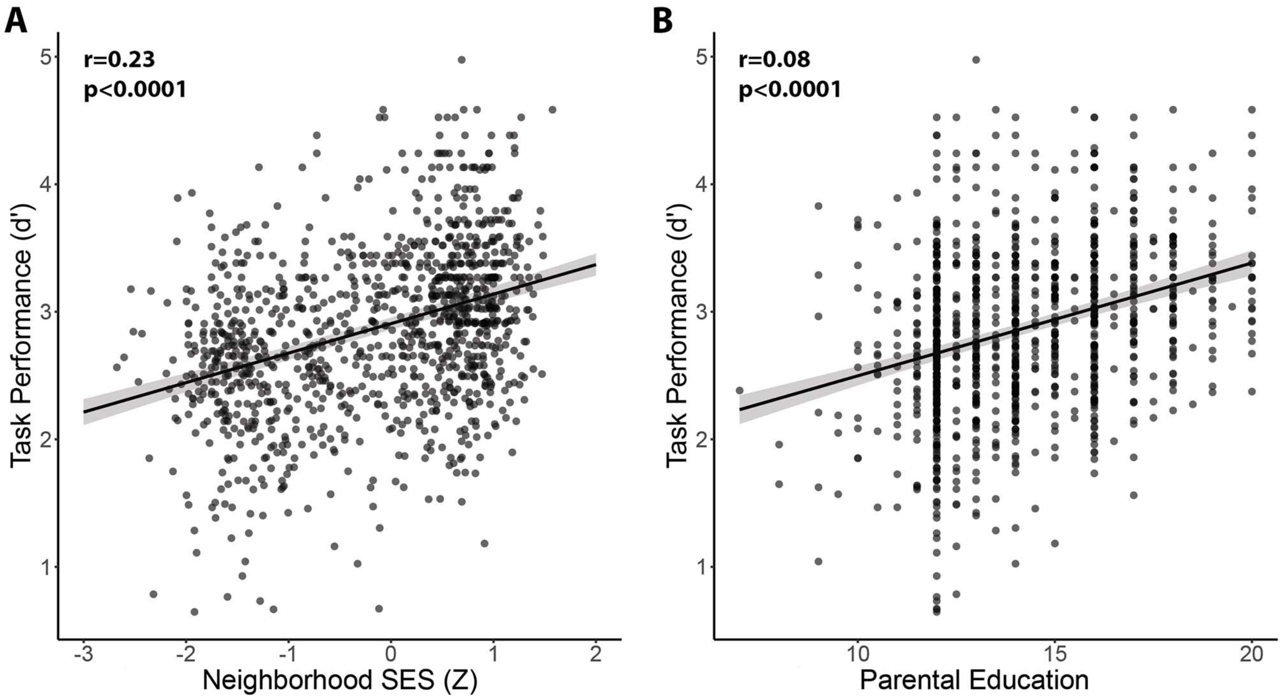

Fig. 5. Both neighborhood SES and parental education are positively associated with WM task performance. WM performance was quantified as *d'* across all *n*-back conditions, while covarying for age and sex.

First, we evaluated how multivariate patterns of activation might mediate the relationship between WM performance and neighborhood SES, independent of parental education (Fig. 6A). In our training sample, bootstrap analysis revealed that 1 PDM had a significant *ab* path after FDR correction ($p\text{-train}_{\text{fdr}} < 0.0001$). Next, we applied the PDM generated in our training data to a held-out test set of 574 participants and tested the significance of the absolute *ab* paths. The *ab* path of the first PDM remained significant in the left out testing sample and survived FDR correction ($p\text{-test}_{fdr} < 0.001$; Table 4A) while controlling for age, sex, and in-scanner motion. As a final step, we examined the spatial distribution of the significant PDMs (Table 5A). The PDM associated with neighborhood-level SES included unique clusters in the ventromedial prefrontal cortex, orbitofrontal cortex, and lateral occipital cortex (Fig. 6B).

Second, we evaluated whether associations between parental education independent of neighborhood SES and WM performance might be similarly mediated by activation patterns. Bootstrap analysis in the training sample revealed 1 PDM had a significant *ab* path after FDR correction ($p\text{-train}_{\text{fdr}} < 0.001$), which remained significant when evaluated in the testing sample, ($p\text{-test}_{fdr} < 0.05$; Table 4B). The PDM associated with parental education included unique clusters in the left dorsomedial prefrontal cortex, right inferior frontal gyrus, and anterior insula (Table 5B, Fig. 6C). Both measures had overlapping activation in the medial prefrontal cortex, bilateral dorsolateral prefrontal cortex, paracingulate, superior parietal cortex, and precuneus (Fig. 6D).

These findings suggest that the association between WM and both neighborhood SES and parental education may in part be mediated by differences in executive system activation, and these multivariate PDMs generalize to unseen data. In both cases, the *a* and *b* path coefficients were positive (note that *a* paths are always

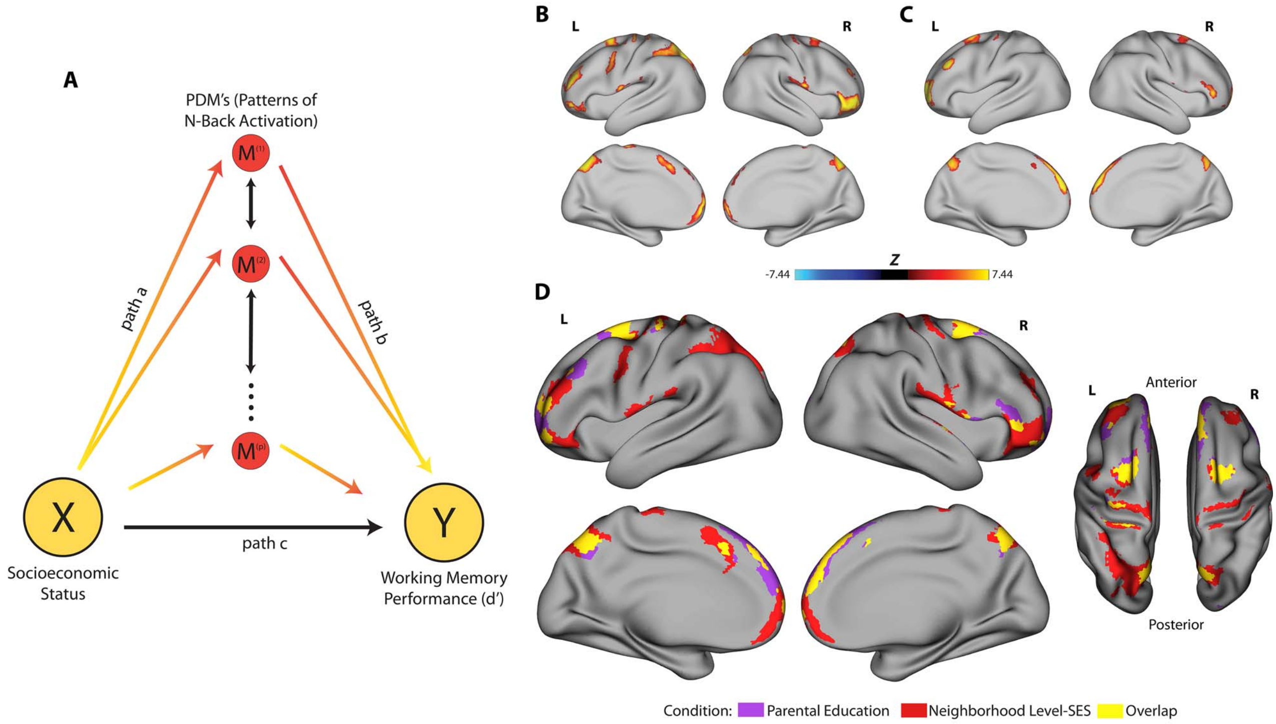

Fig. 6. Multivariate patterns of executive system activation mediate the relationship between neighborhood SES and WM performance. (A) We assessed whether multivariate patterns of activation mediated the relationship between different measures of SES and WM performance using high-dimensional mediation analysis. Large circles labeled X and Y represent independent (SES) and dependent (WM performance) variables. Smaller circles labeled M represent potential principal directions of mediation (PDM's), or patterns of brain activation that mediate the relationship between the dependent and independent variables. This analysis revealed 1 significant pattern of brain activation that mediated the relationship between each measure of SES and task performance (p-train$_{fdr} < 0.01$, p-test$_{fdr} < 0.05$). (B) The relationship between neighborhood SES and task performance was partially mediated by spatially distinct patterns of activation in the ventromedial PFC, orbitofrontal cortex, and parietal cortex. (C) The relationship between parental education and task performance was partially mediated by spatially distinct patterns of activation in the dorsolateral PFC and premotor cortex. (D) Regions of activation associated with both indicators of SES included the dorsolateral PFC, precuneus, and parietal cortex, as well as areas of the motor cortex.

Table 4. Path coefficients, Z-scores, and bootstrapped P-values for train and test data in PDM's 1 & 2.

	Train			Test		
	Coeff	z	P	Coeff	z	P
A. Neighborhood-level SES						
a	845.36000	5.23	<0.0001	575.86020	4.13	<0.0001
b	0.00009	5.14	<0.0001	0.00011	5.25	<0.0001
c'	0.08431	3.41	0.0006	0.11083	4.56	<0.0001
c	0.15783	5.18	<0.0001	0.17583	5.22	<0.0001
ab	0.07352	5.33	<0.0001	0.06500	4.18	<0.0001
B. Parental education						
a	215.45361	3.99	<0.0001	148.15367	2.72	0.0064
b	0.00010	5.20	<0.0001	0.00013	5.35	<0.0001
c'	0.01763	1.57	0.1159	0.03283	2.89	0.0039
c	0.03851	3.17	0.0015	0.05230	3.94	<0.0001
ab	0.02088	3.98	<0.0001	0.01947	2.75	0.0059

fixed as positive by this method), meaning that higher indicators of SES were linked to more activity in the brain regions associated with each PDM, and that activation in these regions was also positively correlated to better WM performance.

Discussion

We found that both higher neighborhood SES and parental education were associated with partially overlapping patterns of greater activation to WM load in multiple regions within the distributed executive

Table 5. Mediation results.

Cluster region	Voxels	Max (Z)	Peak X (mm)	Peak Y (mm)	Peak Z (mm)
A. Neighborhood SES					
Medial prefrontal cortex	3,320	10.28011	0	64	0
Superior parietal cortex, precuneus	2,488	9.881181	−12	−76	58
Left dorsolateral prefrontal cortex	1,216	8.775183	−36	56	24
Supplementary motor area	916	8.545436	−22	−28	74
Primary motor cortex, premotor cortex	819	9.000845	−28	2	66
Right dorsolateral prefrontal cortex	594	8.575234	38	46	38
Right somatosensory cortex	337	6.616755	62	0	6
Premotor cortex	327	8.115926	26	2	68
Paracingulate	276	5.74272	0	18	46
Left somatosensory cortex	195	5.510158	−62	−2	8
B. Parental education					
Medial prefrontal cortex	2,385	8.298537	−4	42	56
Left dorsolateral prefrontal cortex	1,100	8.298537	−32	64	4
Superior parietal cortex, precuneus	861	5.579839	−36	−58	60
Right dorsolateral prefrontal cortex	438	8.076499	26	66	2
Primary motor cortex, premotor cortex	355	8.298537	−28	0	66
Frontal pole	275	6.072657	50	42	6
Premotor cortex	258	6.340738	26	10	66
Left dorsolateral prefrontal cortex	199	6.103474	−44	34	36
Supplementary motor area	195	5.077501	−26	−28	72
Paracingulate	149	5.398947	0	18	48
Lateral occipital cortex	147	4.587439	18	−96	26
Right dorsolateral prefrontal cortex	132	4.764823	30	42	44
Temporal pole	88	5.495156	56	12	−2

system. Our findings indicate that SES measured at the neighborhood level is related to executive system recruitment over and above other related factors, while greater activation related to parental education did not survive sensitivity analyses controlling for exposure to traumatic events or task performance. Furthermore, we demonstrate that multivariate patterns of executive system activation partially mediate the relationship between each indicator of SES and performance on a WM task. These results replicate associations of parental education with cognitive function (Roberts et al. 1999; Goltermann et al. 2021), and provide novel evidence that neighborhood characteristics may influence WM performance through their impact on the brain's executive system.

Higher neighborhood SES and parental education were each associated with increased activation in brain regions associated with WM performance (Crone et al. 2006; Satterthwaite et al. 2013; Samartsidis et al. 2019; Rosenberg et al. 2020). Specifically, SES was associated with activation across regions including the bilateral DLPFC, paracingulate cortex, bilateral superior parietal cortex, and precuneus. These findings expand on earlier work in the same sample, showing reduced regional homogeneity and amplitude of low-frequency fluctuations during resting-state fMRI in frontoparietal regions associated with neighborhood SES (Gur et al. 2019; Tooley et al. 2019). The current results also align with findings that higher family SES, measured by income-to-needs ratio, is associated with increased BOLD activation in the prefrontal cortex during WM tasks (Rosen et al. 2018). Furthermore, this work expands on findings that measures of SES at the neighborhood and family level have distinct effects on measures of neural outcomes, including resting-state connectivity in regions of the brain necessary for cognitive functions like WM (Rakesh et al. 2021). Here, we found that neighborhood SES accounted for a more broad pattern of activation in the distributed executive system than parental education, including the dorsolateral prefrontal cortex and superior parietal cortex.

Notably, we found that our observed pattern of effects was driven by the 2-back task condition, where the greatest WM load was present. This suggests that the relationship between SES and executive system activation is most evident in more cognitively demanding task contexts. No significant relationship between activation and SES was noted in the 0-back condition, which has low WM demands, and mainly serves as a control condition or measure of sustained attention (Miller et al. 2009). While these findings are consistent with prior work from this sample documenting greater activation associated with higher WM load (Satterthwaite et al. 2013), they contrast with another study reporting that low-income adolescents recruit certain regions of the executive system, including the bilateral medial frontal gyrus and intraparietal sulcus, during low-load 0-back trials, whereas high income adolescents recruit these regions only in high-load trials (Finn et al. 2017). These divergent results suggest that future work examining the relationship between SES and WM performance should manipulate WM load over a range of task difficulties to identify load-specific effects.

The current study replicates previous work demonstrating positive associations between SES and performance on a WM task (Noble et al. 2007) and extends prior findings by identifying executive system activation as a significant mediator of this relationship. The findings from our mediation analysis are consistent with other work that identified activation of the middle, inferior, and superior frontal gyri during a WM task as mediators of individual measures of SES and WM performance (Finn et al. 2017; Rosen et al. 2018). However, our use of high-dimensional mediation analysis allowed for a data-driven approach that uncovered distinct multivariate patterns of brain activation that mediated the relationship between SES and WM performance. This approach facilitates the identification of neural mediators that may be contingent on other brain regions, and allows the detection of mediators encoded in distributed patterns of activation (Geuter et al. 2020). We identified 2 patterns of activation that mediated the relationship between SES and WM performance: the first in the medial prefrontal cortex and left and right DLPFC, and the second in the superior frontal gyrus, right middle frontal gyrus, and frontal pole. The DLPFC has previously been linked to performance on high-load WM tasks in lesion studies (Volle et al. 2008; Barbey et al. 2013), as well as in studies of transcranial magnetic stimulation during WM tasks (Brunoni and Vanderhasselt 2014). Furthermore, these results align with previous findings that DLPFC volume mediated differences in SES and executive function in white adults (Shaked et al. 2018).

Notably, our approach used measures of SES defined at the block group ("neighborhood") level, which allowed us to capture facets of an individual's circumstances beyond their immediate family or household environment, yet at a finer geographic resolution than the more commonly used ZIP code. Previous work in public health has found that neighborhood-level factors predict health outcomes over and above measures at the individual level, like chronic kidney disease (Merkin et al. 2007) or coronary heart disease (Pollack et al. 2012). The current data emphasize that neighborhood-level indicators of SES are important to the study of neurocognitive effects as well. Importantly, we found that neighborhood-level SES was associated with executive system activation over and above the effects of individual measures of adversity, such as parental education or exposure to traumatic events. These results suggest that neighborhood-level variables capture important variability not captured at the individual level. As children and adolescents spend significant time in communities outside of their immediate families, it is important that studies of brain development examine neighborhood-level variables.

This study informs the broader literature on how the neighborhood environment supports cognitive development. Studies suggest that children growing up in poorer neighborhoods have less access to higher quality community and educational resources, in terms of school funding and physical infrastructure (Macintyre et al. 1993; Evans 2004), and have parents who are less involved in their children's education, inside and outside of the classroom setting (Benveniste et al. 2003). These relationships are consistent with proposed theories that cognitive stimulation in the home and school environment may scaffold cognitive development, including WM function (Hackman et al. 2015; Rosen et al. 2018; Rosen et al. 2019). Given these considerations, it is possible that children in low-income neighborhoods are not having experiences outside the home useful for developing conventional WM, and that a safe and stimulating neighborhood environment may be equally important to cognitive development.

This hypothesis is consistent with recent work showing that protective measures, like cognitively enriched care or positive parenting, may alter the effects of early life adversity on neural measures such as brain volume (Farah et al. 2021), patterns of myelination and cortical thickness (Hong et al. 2021) or altered brain development in the temporal lobes (Whittle et al. 2017). It is important to note that women in low-wage positions have inflexible and unpredictable schedules, (Dodson and Luttrell 2011; Jacobs and Padavic 2015), and multiple-job holders have less time for sleep or household and leisure activities (Marucci-Wellman et al. 2014). This unpredictability has been associated with higher rates of general work life conflict and time-based conflict (Henly and Lambert 2014), which may contribute to the differences in parenting styles. Furthermore, the conflict between balancing employment and childcare has been associated with higher levels of distress and risk for depression in low-income mothers (Jacobs et al. 2016; Bruns and Pilkauskas 2019).

Furthermore, the link between individual SES and the socially constructed categories of race are well documented (Bryant et al. 2021 Dec 8), as Black Americans have higher unemployment rates (U.S. Bureau of Labor Statistics 2021) and lower median income than white Americans (U.S. Census Bureau 2021). This wealth gap reached record highs after the 2009 recession (Taylor et al. 2011; Shapiro et al. 2014). There are racial disparities in neighborhood quality, such that middle-class Black families live in more disadvantaged neighborhoods than middle-class white families (Adelman 2004). Neighborhood disadvantage can be caused by structural racism, i.e. the policies, ideologies, and institutional practices that result in systemic inequity among racial and ethnic groups (Powell 2007; Gee and Ford 2011; Riley 2018). Factors of structural racism have been hypothesized as the root cause for the academic achievement gap, typically attributed to differences in SES (Merolla and Jackson 2019), as well as found to be related to lower vocational expectations among minority students (Diemer and Hsieh 2008). These social determinants likely play a large role in the relationship between SES and neurocognitive outcomes; however, we were not able to measure this explicitly in the current dataset, as experiences of racism were not measured.

Future studies could aim to separate the effects of structural racism from the effects of adverse environment, by using units of neighborhood measurement that are more informative of the policies in place, for example, school or congressional districts, rather than census tracts (Riley 2018). This is demonstrated in recent work finding that more generous anti-poverty programs decrease SES related differences in hippocampal volume (Weissman et al. 2021). This serves as an important limitation of the current work, as the sample was not collected with the intention of examining these structural factors, and therefore is ill-equipped to tease apart the close relationship of race and both neighborhood SES and parental education within the data. Future studies may consider collecting data tied to more meaningful regional districts, or stratifying their sample by race.

Certain limitations present in the current work should be noted. The data reported in this study are cross-sectional, and the sample was not obtained with the goal of studying early life environmental adversity. Furthermore, our measurement of exposure to traumatic events measures the sum of types of exposures, and cannot account for repeated exposures within a category. The sample is representative of the Greater Philadelphia area, and may not generalize to communities with differing sociodemographic characteristics. Despite strong evidence of BOLD activation during WM as a partial mediator of SES and WM performance, cross-sectional mediation relationships cannot serve as evidence of causality, and other chains of causality between neighborhood SES and cognitive function cannot be ruled out. While our measure of neighborhood SES included various important measures describing an individual's block-level environment, we did not include measures of crime or community violence, which have been shown to vary along with other aspects of SES (Hsieh and Pugh 1993), and may have differential effects on cognitive function (Sheridan and McLaughlin 2014). Additionally, our analysis was limited by the use of parental education as a proxy for family-level SES, rather than parental income. While education level is not always directly related to earnings, they are highly correlated (Davis-Kean 2005) and has been used as a measure of SES in prior work (Noble et al. 2015; Sheridan et al. 2017).

Conclusion

The current study provides evidence that neighborhood-level SES is associated with executive system activation. Additionally, we identify key brain regions that mediate the relationship between neighborhood SES and cognitive performance. These results highlight the importance of neighborhood factors in shaping the executive system and underscore the importance of identifying and protecting against environmental adversity occurring at the community level that contributes to differences in executive functioning. Additionally, given the known relationship between low-SES and risk for psychopathology, (Bradley and Corwyn 2002; Peverill et al. 2021), the current reported association between SES and WM performance supports executive dysfunction as a general risk factor for diverse psychopathology (Wolf et al. 2015; Shanmugan et al. 2016). Future research may investigate targeted interventions, including community based-interventions, which may be utilized to improve WM performance.

Acknowledgments

The authors would like to thank the research participants and their families. Additionally, we would like to specifically acknowledge the contributions of Black families, who's contributions to psychology and psychiatry have been historically unacknowledged.

Supplementary material

Supplementary material is available at *Cerebral Cortex* online.

Funding

This work was supported by the National Institutes of Health (T32MH014654 to B.L., F31 MH123063-01A1 to A.P., R01MH113550 to L.P., R01MH120174 to D.R.R., R01MH119185 to D.R.R., and R56AG066656 to D.R.R., R01MH113565 to D.H.W., R01MH117014 to D.H.W., M.E.C., R.C.G., R.E.G., and T.M.M., R37MH125829 to T.D.S., R01MH120482 to T.D.S., R01MH112847 to T.D.S., R01MH113550 to T.D.S., and RF1MH116920 to T.D.S.); National Institute of Biomedical Imaging and Bioengineering (R01EB016061 to M.A.L., R01EB022573 to T.D.S); National Institute of Aging (R56AG066656 to D.R.R.); and the Brain & Behavior Research Foundation (2020 NARSAD Young Investigator Award to L.P.)

Conflict of interest statement. Dr. Barzilay serves on the scientific board and reports stock ownership in 'Taliaz Health', with no conflict of interest relevant to this work. All other authors declare no competing financial interests.

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