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Neurocognitive basis of deductive reasoning in children varies with parental education

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Abstract

The neurocognitive basis of elementary academic skills varies with parental socioeconomic status (SES). Little is known, however, about SES-related differences underlying higher-order cognitive skills that are critical for school success, such as reasoning. Here we used fMRI to examine how the neurocognitive basis of deductive reasoning varies as a function of parental education in school-aged children. Higher parental education was associated with greater reliance on the left inferior frontal gyrus when solving set-inclusion problems, consistent with other work suggesting that these problems might more heavily rely on verbal systems in the brain. In addition, children who are at the lower end of the parental education continuum, but have higher nonverbal skills relied on right parietal areas to a greater degree than their peers for solving set-inclusion problems. Finally, lower parental education children with higher verbal or nonverbal skill engaged dorsolateral prefrontal regions to a greater degree for set-inclusion and linear-order relations than their peers. These findings suggest that children with lower parental education rely on spatial and cognitive control mechanisms to achieve parity with their peers with parents who have more education. Better understanding variability in the neurocognitive networks that children recruit as a function of their parental factors might benefit future individualized interventions that best match children's characteristics.

KEYWORDS
deductive reasoning, fMRI, nonverbal, parental education, socioeconomic status, verbal

1 | INTRODUCTION

Children from disadvantaged backgrounds fall behind their peers in their academic performance. SES-related disparities in academic readiness are present even before children enter school and continue to persist or even widen over time (e.g., Brooks-Gunn & Duncan, 1997; White, 1982). Recent work emphasized the need to identify the neurocognitive mechanisms underlying academic disparities to better explain the nature of the differences observed.

Behavioral measures might reveal the extent of SES-related disparities, while neuroimaging work might inform by revealing the component neurocognitive processes that underlie behavioral differences. Examining SES-related differences in the neurocognitive networks might then potentially pinpoint targets for intervention. Here, we aim to examine how the neurocognitive basis of deductive reasoning, a skill central for school success, varies as a function of parental education—a widely used indicator for SES (Bradley & Corwyn, 2002).

2 | SES-RELATED DIFFERENCES IN THE VERBAL AND NONVERBAL SYSTEMS IN THE BRAIN

SES-related differences in children's language and literacy skills are well-established (Hoff, 2006; Huttenlocher, Waterfall, Vasilyeva, Vevea, & Hedges, 2010; Noble, McCandliss, & Farah, 2007). Differences in language abilities are present as early as 18 months of age (Fernald, Marchman, & Weisleder, 2013) and are observed at school entrance, that is, kindergarten (Bradley & Corwyn, 2002). This gap widens as children progress in elementary school (Brooks-Gunn & Duncan, 1997; National Center for Education Statistics, 2011; National Mathematics Advisory Panel, 2008). For example, by fifth grade, lower SES children may be as many as three grade-levels below in their reading achievement compared with their higher SES peers (Cooper, Borman & Fairchild, 2010).

In line with behavioral work, neuroimaging literature consistently reports SES-related differences in neurocognitive systems related to academic performance (for reviews, see Farah, 2017; Hackman & Farah, 2009; Tomalski & Johnson, 2010). Prior work emphasized SES-related differences in neurocognitive networks that support verbal processing. Structural neuroimaging studies show that lower SES is associated with reduced gray matter in brain regions underlying language comprehension and production, such as left perisylvian regions (Brito & Noble, 2018; Noble et al., 2015; Noble, Houston, Kan, & Sowell, 2012), and brain regions that underlie reading, such as bilateral occipitotemporal regions (Jednoróg et al., 2012; Mackey et al., 2015) as well as to changes in brain structure over time (Piccolo et al., 2016). Functional neuroimaging studies using language tasks reveal similar SES-related differences (Romeo et al., 2018; Younger, Lee, Demir-Lira, & Booth, 2019). For example, Raizada, Richards, Meltzoff, and Kuhl (2008) found that the asymmetry in the activity of the left perisylvian regions during a rhyming task—related to the maturation of language processing—was less pronounced in children from disadvantaged SES backgrounds compared with those from more advantaged SES backgrounds. SES-related differences in the underlying neurocognitive verbal systems are apparent beyond language and literacy tasks. When solving arithmetic tasks, for children at the higher end of the SES continuum, greater recruitment of the verbal systems in the brain (e.g., lMTG, lIFG) is correlated with higher current and future math skill compared with children at the lower end of the SES continuum (Demir, Prado, & Booth, 2015; Demir-Lira, Prado, & Booth, 2016).

SES-related differences might not be uniform across different domains. Studies that examined SES-related differences across domains revealed that disparities in nonverbal tasks might be less pronounced compared with verbal tasks. Behavioral studies show that SES-related differences are larger when children are presented with tasks in a verbal format (e.g., verbally presented number combinations) compared with when the same children are presented with a nonverbal format (e.g., nonverbal calculations with discs) (Jordan, Huttenlocher, & Levine, 1992; Jordan & Levine, 2009). Similarly, Farah and colleagues assessed SES-related differences in a wide range of neurocognitive skills in 10-to 13-year-old children using a battery of standardized tasks (Farah et al., 2006). Significant SES-disparities were observed on linguistic tasks, typically tapping into left perisylvian regions. However, in the same study, SES-disparities were smaller/nonsignificant on tasks involving spatial and visual processing (which rely on parietal and occipitotemporal regions, respectively). Consistent with these behavioral studies, structural neuroimaging studies report relations of SES to brain structure in language-relevant regions, such as left IFG and STG, even in the absence of relations to total cortical volume or white matter volume (Noble et al., 2012). Functional neuroimaging studies including both language and visuospatial tasks revealed significant SES differences on language tasks but not on visuospatial tasks within the same group of children (e.g., Demir et al., 2015). Overall, however, it is important to highlight that the differential relations should be interpreted with caution since the literature on SES-related differences in spatial thinking is relatively sparse and underpowered.

Recent work showed that children from lower SES backgrounds might recruit visuospatial systems in the brain to a greater extent to perform on par with peers on various academic tasks. For example, when solving single-digit arithmetic tasks, for children at the lower end of the SES continuum, current and future math skill were correlated with greater reliance on visuospatial systems in the brain (e.g., rIPL, rSPL) compared with children at the higher end. Importantly, SES-related differences were observed even in the absence of behavioral differences (Demir et al., 2015; Demir-Lira et al., 2016). Structural neuroimaging studies showed similar patterns. In a recent study using DTI, reading skills of children from lower SES background were positively related to fractional anisotropy (reflecting tract coherence) in the right inferior longitudinal fasciculus, which is considered to support general visuospatial processing. In contrast, reading skills of children from higher SES backgrounds were positively related to fractional anisotropy in left hemisphere tract clusters (including inferior longitudinal fasciculus) considered to support reading skill (Gullick, Demir-Lira, & Booth, 2016). Overall, these results suggest that children from different SES backgrounds might show adaptations and rely on different systems in the brain to perform the same task.

3 | NEUROCOGNITIVE BASIS OF DEDUCTIVE REASONING

The majority of the prior work on SES-related differences focused on basic cognitive processes, such as working memory, executive function, or elementary academic skills, such as single-word reading or single-digit arithmetic. Ultimately, while most children will successfully learn to complete such elementary academic tasks, gaps in unconstrained, complex academic tasks might remain (McCormick et al., 2020; Paris, 2005). Such tasks range from the comprehension of complex scientific texts to writing essays or engaging in debates. Thus, better characterizing the neurocognitive basis of later emerging complex academic skills is a fundamental first step in addressing persistent disparities in school performance.

A skill that has an extended trajectory and is crucial for academic performance is deductive reasoning. Deductive reasoning can be defined as the ability to reach necessary conclusions from given premises. Deductive reasoning plays a central role in academic learning (Pagani, Brière, & Janosz, 2017; Zippert, Clayback, & Rittle-Johnson, 2019). For instance, deductive reasoning supports linguistic skills such as word learning (Halberda, 2006) and text comprehension (Lea, O'Brien, Fisch, Noveck, & Braine, 1990). It is also fundamental to the growth of math skills in children, such as algebra or geometry (Ayalon & Even, 2008; Green, Bunge, Briones Chiongbian, Barrow, & Ferrer, 2017; Nunes, Bryant, Evans et al., 2007; Singley & Bunge, 2014). As a result, difficulties with deductive reasoning have been associated with both mathematical learning difficulties (Morsanyi, Devine, Nobes, & Szűcs, 2013) and language impairments (Katsos, Roqueta, Estevan & Cummins, 2011).

Over the past decades, several neuroimaging studies have explored the neural substrates of deductive reasoning in adults (Holyoak & Monti, 2021; Prado, Chadha, & Booth, 2011; Wendelken, Ferrer, Whitaker, & Bunge, 2016). These studies have often led to inconsistent results. For example, it has been claimed that deductive reasoning relies on brain regions supporting linguistic processing (Reverberi et al., 2007; Reverberi et al., 2012), visuospatial processing (Fangmeier, Knauff, Ruff, & Sloutsky, 2006; Knauff, Fangmeier, Ruff, & Johnson-Laird, 2003), or on "core" brain regions that are independent from both verbal and spatial processing (Coetzee & Monti, 2018; Monti, Osherson, Martinez, & Parsons, 2007; Monti, Parsons, & Osherson, 2009). To account for these conflicting results, some have proposed that deductive reasoning may be supported by heterogeneous brain mechanisms that are dynamically configured depending on the task (Goel, 2007; Prado, 2018; Prado et al., 2011). For example, the underlying networks supporting deductive reasoning appear to vary depending on the logical form of the premise. Notably, arguments that contain linear-order relations (*Tom is taller than Bill, Bill is taller than John. Tom is taller than John.*) have been associated with spatial regions of the parietal cortex, most likely because linear premises are relatively easy to map on spatial representations (Prado et al., 2011; Prado, Mutreja, & Booth, 2013). On the contrary, arguments that contain set-inclusion relations (*All tulips are flowers. All flowers are plants. All tulips are plants.*) have been associated with verbal regions of the left prefrontal cortex, most likely because premises with quantifiers are more difficult to map on spatial representations (Prado et al., 2011, 2013).

This task-dependency of the deductive reasoning network has also been observed in children. Similar to adults, a study on school-age children found that arguments that contained set-inclusion relations were associated with greater activity in a region of the left IFG, considered to also be involved in the maintenance of verbal information. In contrast, arguments that contained linear-order relations were associated with greater activity in regions of the parietal cortices (SPL and Precuneus), considered to be involved in spatial processing and mental imagery (Mathieu, Booth, & Prado, 2015). Consistent with the idea than linear-order arguments are association with parietal regions, structural neuroimaging work also showed a positive correlation between gray matter density in parietal cortices and performance on linear-order arguments in adolescents and adults (Modroño et al., 2019).

4 | DEDUCTIVE REASONING AND SES

Despite the importance of deductive reasoning for development and academic success, little is known about the way its underlying neural mechanisms relates to differences in SES. To our knowledge, only one structural neuroimaging study examined whether the relations between brain structure and reasoning vary as a function of SES. Bilateral cortical thickness of rostrolateral prefrontal cortex (RLPFC) was found to be positively correlated with reasoning ability in children from lower-SES backgrounds, but not in children from higher-SES backgrounds (Leonard et al., 2019). However, Leonard et al. (2019) only investigated matrix reasoning, which is a measure of inductive (i.e., more specifically analogical) rather than deductive reasoning. Thus, it is unclear how results extend to deductive abilities. Further, Leonard et al. (2019) included structural neuroimaging only. To our knowledge, there are no prior functional neuroimaging studies that examine how the neurocognitive basis of reasoning vary by SES as children are engaged in the task. To fill this gap, here we examine the main effect of SES on the functional basis of deductive reasoning.

In the current study, we asked whether the neurocognitive basis of deductive reasoning differs along the SES continuum. We used parental education as our measure of SES because it 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). We tested brain regions involved in the processing of linear-order and set-inclusion relations during the elementary school period. Prior literature suggests that set-inclusion relations may more heavily rely on verbal compared with spatial regions, whereas linear-order relations may more heavily rely on spatial compared with verbal regions. Thus, given that previous behavioral research has shown the larger SES effects on verbal skills, we expected to observe the most robust parental education-related differences in the neurocognitive basis of set-inclusion relations compared with linear-order relations. Moreover, we expected that children with higher parental education and with higher skill would engage verbal regions to a greater degree for these set inclusion problems. In contrast, we expected that children whose parents had lower education and who were higher skill might adapt by engaging spatial regions to a greater degree.

5 | METHOD

5.1 | Participants

Participants were 49 children, ages 9 to 14, recruited from the greater Chicago area. According to parental reports, children had no prior history of neurological disease, psychiatric disorders, learning disabilities,

or attention deficit hyperactivity disorder. Children were all right-handed, native English speakers with normal hearing and normal or corrected-to-normal vision. Informed consent was obtained from parents and children, which was approved by the Northwestern University Institutional Review Board. Data from 10 subjects were excluded because of excessive head movement in the scanner (see criteria below, *n* = 6) or because they did not understand the task or did not complete the entire experiment (*n* = 4). Therefore, the final sample consisted of 39 children (mean = 11.4 years, *SD* = 1.5, 21 females).

5.2 | Socioeconomic status

Parental SES information was measured by caregiver education level. Education level of the caregivers was measured categorically with values ranging between 10 (less than high school) to 18 (graduate degree). The average education score for our sample was 15 years (*SD* = 1.8), with a range from 12 to 18 years, corresponding to a college degree. For 34 children, education level of both the mother and father was provided, for the remaining four only education level of the mother was provided. For the former group, average education was used. For the remaining, the education of the mother was used. Mother and father education were positively and significantly correlated with each other, *r* = .63, *p* < .001.

5.3 | Standardized testing

Children participated in a comprehensive standardized testing session and were administered Wechsler Abbreviated Scale of Intelligence (Wechsler, 1999). We measured verbal skills with the verbal composite score based on Vocabulary and Similarities subtests. We measured nonverbal skills with a composite score based on Block design and Matrix reasoning subtests. Similarities subtest requires children to describe how two words are alike/similar. Vocabulary subtest requires children to define a provided word. Block Design subtest requires children to put together red-and-white blocks in a pattern according to a displayed model. Matrix Reasoning subtest requires children to select the picture that fits the array of pictures with one missing square from five options. During the same session, children were also administered other tests of language, reading and math that are not reported here.

5.4 | Reasoning tasks

In each trial, participants were presented with a deductive argument that contained three premises and one conclusion, such as (1) and (2):

1. Bud is slower than Joe
   Joe is slower than Liz.
   Liz is slower than Rex.
   Therefore, Bud is slower than Rex

2. All larns are white
   All white things are tall.
   Bud is a larn.
   Therefore, Bud is tall.

Participants had to decide whether the conclusion of each argument necessarily followed from the premises. Arguments included one of two types of relations: linear-order or set-inclusion relations. Linear-order arguments described a linear-ordering of four imaginary characters. In linear-order arguments, the same comparative adjective was used throughout and consisted of one of the following: slower, faster, shorter, taller, younger, older, smaller, and bigger. See example (1) above. Set-inclusion arguments described the inclusion of an imaginary character within two different classes. In set-inclusion arguments, the first class was characterized by a one-syllable name that was different in each problem (e.g., gofs, trabs, larns, and progs). The second class was described by the following adjectives: tall, short, big, small, old, young, fast, slow, brown, red, black, blue, green, white, pink. See example (2) above. Conclusions of arguments required either the integration of all three premises (e.g., arguments [1] and [2] above), or the integration of only two of the premises (e.g., consider the conclusions *Bud is slower than Liz* and *Bud is white* in arguments [1] and [2] above, which would require integrations of two premises only].

Conclusions could be one of four types: (a) valid and affirmative (18 linear-order trials and 18 set-inclusion argument trials) (e.g., arguments [1] and [2] above], (b) invalid and affirmative (six linear-order and six set-inclusion argument trials) (e.g., *Bud is slower than Joe, Joe is slower than Liz, Liz is slower than Rex, therefore Rex is slower than Bud; All larns are white, All white things are tall, Bud is tall, therefore Bud is a larn*), (c) valid with negation (six linear-order and six set-inclusion argument trials) (e.g., *Bud is slower than Joe, Joe is slower than Liz, Liz is slower than Rex, therefore Rex is not slower than Bud; All larns are white, All white things are tall, Bud is not tall, therefore Bud is not a larn*), or (d) invalid with negation (six linear-order and six set-inclusion argument trials) (e.g., *Bud is slower than Joe, Joe is slower than Liz, Liz is slower than Rex, therefore Bud is not slower than Rex; All larns are white, All white things are tall, Bud is a larn, therefore Bud is not tall*). Taken together, there were 36 trials per task divided across two runs. We included a variety of arguments to make the task as unpredictable as possible and encourage children to genuinely engage in reasoning during the experiment. In our analysis, we focused on the most straightforward arguments in which the conclusion was valid and affirmative. Only arguments for which a correct response was provided were included in the analyses (Prado, Noveck, & Van Der Henst, 2010; Reverberi et al., 2007). Other arguments were considered fillers.

5.5 | Experimental protocol

Informed consent was obtained from the participants. Participants were first administered standardized tests and then they participated in a practice session where they practiced all trials of the tasks described above. During the practice sessions, participants were presented with five arguments with linear-order relations and five

arguments with set-inclusion relations. Different sets of stimuli were used for practice and fMRI session. Participants also learned to minimize head movements in a mock fMRI scanner (with feedback from an infrared tracking device).

The fMRI scanning session took place within 1 week of the practice session. Following training, in the fMRI scanner, participants performed two runs of each type of arguments. The order of the tasks was counterbalanced across participants. The timing and order of trial presentation within each run was optimized for estimation efficiency using optseq2 (http://surfer.nmr. mgh.harvard.edu/optseq/). Behavioral responses were recorded using a keypad placed below the right hand. In reasoning trials, participants responded with their index finger if the conclusion was valid and with their middle finger if it was invalid. Stimuli were generated using E-prime software (Psychology Software Tools, Pittsburgh, PA) and projected onto a screen that was viewed by the participants through a mirror attached to the head coil.

5.6 | Stimulus timing

In reasoning trials, each premise and conclusion appeared on the screen one at a time and remained on the screen until the end of the trial. Each sentence was also simultaneously spoken through headphones to facilitate comprehension. The first premise was presented at 0 s, the second at 2 s, the third at 4 s, and the conclusion was displayed at 6 s (see Figure 1). Response time (RT) was calculated from the presentation of the conclusion to the button press. The end of the trial occurred either when a button was pressed or 8 s after the onset of the conclusion if the participant did not respond. Variable periods of passive visual fixation (ranging from 2,600 to 3,400 ms) were added between each trial. Furthermore, each run ended with 22 s of passive visual fixation. Those fixation periods (during which participants fixated a cross at the center of the screen) constituted the baseline.

5.7 | fMRI data acquisition

Images were collected with a Siemens Trio 3 T MRI scanner (Siemens Healthcare, Erlangen, Germany). The fMRI blood oxygenation level dependent signal was measured with a susceptibility weighted single-shot echo planar imaging sequence. Imaging parameters were: time repetition (TR) = 2,000 ms, time echo (TE) = 20 ms, flip angle = 80°, matrix size = 128 × 120, field of view = 220 × 206.25 mm, slice thickness = 3 mm (0.48 mm gap), number of slices = 32, voxel size = $2 \times 2 \times 4$ mm^3. In addition to the functional scans, a high-resolution T1-weighted whole-brain anatomical volume was collected for each participant (TR = 1,570 ms, TE = 3.36 ms, matrix size = 256 × 256, field of view = 240 mm, slice thickness = 1 mm, number of slices = 160).

5.8 | fMRI data analyses

5.8.1 | Data preprocessing

Data analysis was performed using the Statistical Parametric Mapping software (SPM8; Functional Imaging Laboratory, UCL, London, UK, http://www.fil.ion.ucl.ac.uk/spm). The first six scans of each run were removed to allow for magnetization equilibration effects. The remaining functional images were corrected for slice acquisition delays and realigned to the first image of the first run to correct for head movements. Images were then spatially smoothed with a Gaussian filter equal to twice the voxel size ($4 \times 4 \times 8$ mm^3 full width at half maximum). ArtRepair, an artifact repair software (Mazaika, Hoeft, Glover, & Reiss, 2009) (http://cibsr.stanford.edu/tools/ human-brain-project/artrepair-software.html), was used to help remove motion from the functional images prior to normalization. ArtRepair improves the quality of fMRI data containing high motion by removing residual motion fluctuation and detecting scans with significant artifact. Volumes with rapid scan-to-scan movements of greater than 3 mm were repaired by interpolation of the two nearest nonrepaired scans. We verified whether the repaired volumes corresponded to arguments of interest or filler arguments. A subject was excluded from further analysis if more than four arguments of interest were associated with repaired volumes. Finally, functional images were normalized into the standard Montreal Neurological Institute (MNI) space. This was done in two steps. First, after coregistration with the functional data, the structural image was segmented into gray matter, white matter, and cerebrospinal fluid by using a unified segmentation algorithm
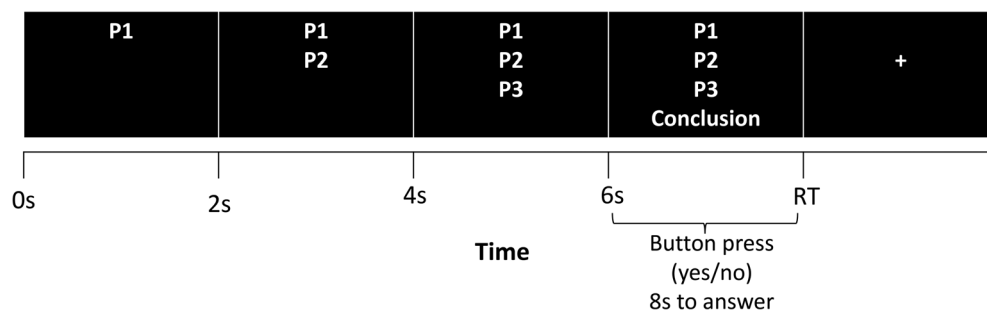

FIGURE 1 Experimental procedure. Three premises (P1, P2, and P3) and one conclusion appeared one by one every 2 s and remained on the screen until the end of the trial. Participants were asked to evaluate the conclusion by pressing one of the two response keys (yes/no). After each trial, a period of visual fixation was presented during which a cross remained at the center of the screen

(Ashburner & Friston, 2005). Second, the functional data were normalized to the MNI space by using the normalization parameters estimated during unified segmentation (normalized voxel size, $2 \times 2 \times 4 \text{ mm}^3$).

5.8.2 | First-level analyses

Statistical analysis was performed according to the General Linear Model (GLM, Josephs et al., 1997). Reasoning arguments were modeled as epochs with onsets time locked to the presentation of the first premise and offsets time locked to the button press. Therefore, premises and conclusion were modeled within the same block. Arguments of interest in which subjects provided a correct response were sorted by type of relation (linear-order, set-inclusion). Regressors of no interest coded all the other trials (i.e., fillers and incorrect responses on arguments of interest). Additionally, a parametric regressor coding for RTs across trials was included to rule out the possibility that any difference between conditions could be explained by trial-by-trial variation in performance. Linear statistical contrasts were subsequently entered into second-level analyses. Epochs were convolved with a canonical hemodynamic response function. The time series data were high-pass filtered (1/128 Hz), and serial correlations were corrected using an autoregressive AR (1) model.

5.8.3 | Second level analyses

The goal of this study was to assess the relations between parental education and processing of logical relations containing linear-order and set-inclusion arguments. We also examined if the role of parental education would vary as a function of behavioral skill—specifically whether verbal and nonverbal skills would interact with parental education in predicting the neural basis of deductive reasoning. To evaluate the relations of parental education, behavioral skill and their interactions to the neural bases of logical reasoning, we created separate second-level voxelwise regression models. In each model, parental education constituted the regressor of interest. We also included a behavioral measure of verbal or nonverbal skill in separate models. As the behavioral measure of verbal skill, we used the composite of the Similarities and Vocabulary subtests on the WASI. As the behavioral measure of nonverbal skill, we used the composite of the Matrix Reasoning and Block Design subtests on the WASI. Overall, we ran four separate models—analyses were conducted separately for each logical argument type (linear-order, set-inclusion) and separately for each measure of behavioral skill (verbal, nonverbal). First, to examine the relations between parental education, behavioral skill, and the neural bases of logical reasoning, we identified the brain regions that showed an increase or a decrease in activity during the evaluation of linear-order or set-inclusion arguments with parental education across subjects. Second, to evaluate whether the role of parental education interacts with verbal or nonverbal skill, we systematically modeled an interaction term—this enabled us to identify the brain regions that

showed an increase or decrease in activity with the interaction of parental education and verbal or nonverbal skill across subjects. Given our limited sample size, the current study might be underpowered to detect interaction effects and the analyses on interactions between SES and skill should be considered exploratory. Age was also included as a covariate in all analyses. Overall, for each model, we had behavioral skill, parental education, an interaction term and age. For all analyses an implicit baseline of general task activation was used. A FWE-corrected cluster-level threshold of $p = .05$ (defined using a voxel-level threshold of $p = .001$) was applied to all whole-brain statistical maps to assess brain activations.

5.8.4 | ROI definition

Following whole brain analyses, we also identified activation in prespecified regions of interest found to be involved in processing linear-order and set-inclusion arguments in previous studies of children and adults (Mathieu et al., 2015; Prado et al., 2011, 2013). These regions included bilateral Superior Parietal lobule and left Inferior Frontal Gyrus. Bilateral SPL was selected because it is involved in the overlap of linear-order processing and spatial maintenance (Mathieu et al., 2015; Prado et al., 2011, 2013). Left IFG was selected because it is involved in the overlap of set-inclusion processing and verbal maintenance (Mathieu et al., 2015; Prado et al., 2011, 2013). We used a small volume correction (SVC) procedure to examine activity in these regions. All regions were defined with the WFU PickAtlas Tool (Maldijan, Laurienti, Kraft, & Burdette, 2003). All coordinates are reported in MNI space and approximate Brodmann areas are identified by the Talairach Daemon software (http://www.talairach.org/daemon.html). Activity in these regions was considered significant if it was below a cluster-level FWE threshold of $p < .05$ with a voxel-level threshold of $p = .001$ across the anatomical mask. SPM was used to extract eigenvariates from activated clusters, which were then used for visualization.

6 | RESULTS

6.1 | Behavioral results

Table 1 summarizes the performance on standardized tests and in-scanner reasoning tasks. As presented in Table 2, we also examined the correlations between age, behavioral measures of in-scanner performance (accuracy and RT), scanner motion, verbal and nonverbal skill, and parental education. Parental education did not correlate with age or any of the behavioral measures of in-scanner performance or scanner motion. Parental education was correlated with the WASI spatial composite and there was a trend for the WASI verbal composite. The verbal and spatial composite were significantly correlated with each other, but were not correlated with any behavioral in-scanner measures or motion, except for a trend between the spatial composite and set-inclusion accuracy. Set-inclusion accuracy was

TABLE 1 Performance on standardized tests and in-scanner reasoning tasks

	Average (SD)	Range
Standardized test performance		
WASI verbal composite	115 (15)	87–148
WASI nonverbal composite	113 (14)	88–138
In-scanner reasoning task performance		
Linear-order accuracy	0.84 (0.07)	0.67–0.93
Set-inclusion accuracy	0.76 (0.10)	0.52–0.93
Linear-order RT (ms)	1,419 (327)	815–2,319
Set-inclusion RT (ms)	2059 (383)	1,247–2,873

TABLE 2 Bivariate correlations between age, behavioral measures of in-scanner performance (accuracy and RT), scanner motion, verbal and nonverbal skill and parental education

	2	3	4	5	6	7	8	9
1. Parental education	−0.199	0.299~	**0.332***	0.064	0.059	−0.074	0.158	−0.173
2. Age	1	−0.045	−0.192	**0.374***	0.252	−0.067	**−0.379***	0.255
3. WASI verbal composite		1	**0.392***	0.17	0.142	−0.222	−0.079	**−0.354***
4. WASI nonverbal composite			1	0.135	0.289~	0.07	0.076	−0.143
5. Linear-order accuracy				1	0.212	0.08	−0.252	0.135
6. Set-inclusion accuracy					1	**0.369***	0.049	0.289
7. Linear-order RT (ms)						1	**0.363***	−0.062
8. Set-inclusion RT (ms)							1	−0.167
9. Scanner motion								1

*$p < .05$, ~ $p < .10$.

positively correlated with RT on linear-order problems. RT on the two reasoning tasks were correlated with each other. There were no significant differences by sex on any of the demographic variables (parental education, age), standardized measures (WASI nonverbal and verbal), or on behavioral measures (accuracy, RT), all p's > .05.

6.2 | Set-inclusion arguments: Role of parental education, verbal and nonverbal skill and their interaction

6.2.1 | Main effects of task

First, we identified brain regions involved in processing of set-inclusion arguments. At the whole brain level, set-inclusion arguments activated a wide network including left IFG, MTG, SFG, SPL, and MOG as well as right STG, MOG, SPL, and thalamus (Figure 2).

6.2.2 | Parental education and verbal skill

Next, we identified the brain regions that showed an increase or a decrease in activity during the evaluation of set-inclusion arguments with parental education, verbal skill and their interaction across

subjects using the contrast of (set-inclusion—baseline). Following the whole brain analysis, we used a small volume correction (SVC) procedure to examine activity within the ROIs. Activity within the masks (left IFG and bilateral SPL) was considered significant if it was below a FWE threshold of $p < .05$ across this mask using small-volume correction (SVC).

Table 3 lists brain regions that showed activation related to parental education during set-inclusion problems. At the whole brain level, parental education tended to be associated with activity in one cluster of left IFG. Using SVC, parental education was significantly related to activation in this cluster. For visualization purposes, we extracted the eigenvariate from the significant cluster and plotted it against parental education. This plot showed that the higher the parental education, the greater is the peak cluster activation in left IFG (see Figure 3). Activity within bilateral SPL mask did not reach significance. There were no regions that showed a significant negative relation to parental education or a relation to the interaction between parental education and verbal skill.

6.2.3 | Parental education and nonverbal skill

Second, we identified the brain regions that showed an increase or a decrease in activity during the evaluation of set-inclusion with respect
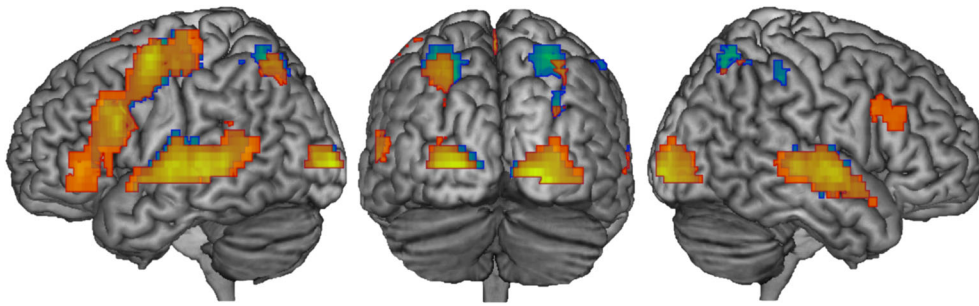
FIGURE 2 Main effect of task for set-inclusion (red) and linear-order (blue) problems. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI normalized anatomical brain

TABLE 3 Brain regions that showed activation related to parental education, verbal skill and nonverbal skill in the set-inclusion and linear-order reasoning tasks

	Anatomical location	∼BA	MNI coordinates			z-score	Cluster size (mm³)	Whole-brain cluster level FWE-corr	SVC cluster-level FWE-corr
			X	Y	Z				
	Set-inclusion								
Parental education	L. IFG	46	−42	36	10	3.86	49	0.07	0.005
Parental education X nonverbal skill	L. SPL/precuneus	7/19	−18	−78	42	4.81	121	0.001	0.008
	L. Middle occipital	19	−40	−66	6	4.53	84	0.007	n/a
	R. Precuneus	30	22	−52	2	4.24	66	0.023	n/a
	R. MFG	6	40	0	42	4.8	61	0.032	n/a
	R. MFG	8	28	16	38	4.01	61	0.032	n/a
	Linear-order								
Parental education X verbal skill	Right MFG	8	26	12	46	4.41	71	0.03	n/a

Note: Size, number of 2 x 2 x 4 mm³ voxels.

Abbreviations: ∼BA, approximate Broadmann Area for the peak coordinate; L., left; MNI, Montreal Neurological Institute; R., right; SVC, small volume correction.
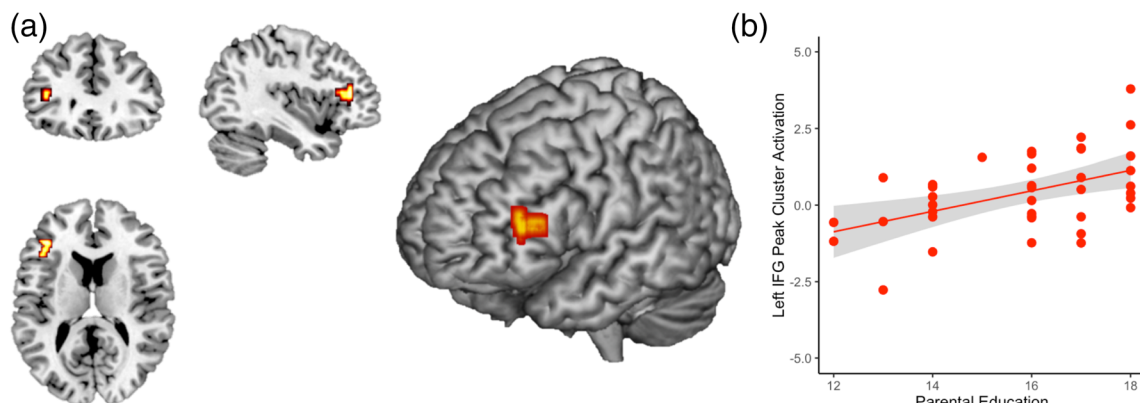

FIGURE 3 Relations to parental education for set-inclusion problems. (a) Activity with small volume correction in left IFG showed a positive relation to parental education. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI normalized anatomical brain. (b) Eigenvariates was extracted from the peak of the significant cluster in left IFG (x = −42, y = 36, z = 10) and plotted against parental education for visualization purposes only

to parental education, nonverbal skill and their interaction across subjects using the contrast of (set-inclusion−baseline). There were no brain regions that showed significant negative or positive relation to parental education. The interaction between parental education and

nonverbal skill was negatively related to activation in multiple clusters—more specifically the relation between nonverbal skill and activation in these clusters increased as parental education decreased. These included the left SPL/precuneus at the whole brain level which

was confirmed with SVC using the bilateral SPL mask. Also, at the whole brain level, the interaction was negatively related to activation in left middle occipital, right precuneus and right MFG (see Table 3). Activity within left IFG mask did not reach significance. There were no regions that showed a significant negative relation to parental education or related to the interaction between parental education and verbal skill.

To better characterize the interaction between parental education and nonverbal skill, for visualization purposes only, we divided the children into two groups based on median education, 16 years (lower than the median constituting lower parental education, and at or higher than the median constituting higher parental education). We then extracted the eigenvariate from the significant clusters described above and plotted it against nonverbal skills for the two parental education groups. This plot showed that for children below the median on parental education, nonverbal skills appears to be positively associated with activity in left SPL and right MFG, but the relation appears to be negative for children with above the median parental education (see Figure 4).

As discussed above, verbal and nonverbal skill was significantly correlated with each other. To further test the specificity of the association observed with nonverbal skill, we ran an additional model controlling for verbal skill. This enabled us to see if the interaction between nonverbal skill and parental education would remain even after controlling for children's verbal skill level. The interaction term between parental education and nonverbal skill was negatively related to activation in the same set of clusters reported above: left SPL/precuneus (x = −18, y = −78, z = 42, BA = 7/19, k = 68, z = 4.47, cluster-level pFWE-corr = .021, height threshold <0.001), left middle occipital (x = −40, y = −66, z = 6, BA = 19, k = 61, z = 4.47, cluster-level pFWE-corr = .033, height threshold <0.001), right precuneus (x = 22, y = −52, z = 2, BA = 30, k = 66, z = 4.24, cluster-level pFWE-corr = .021, height threshold <0.001). In the model controlling for verbal skill, the interaction effects in right MFG ceased to be significant but remained as a trend (x = 28, y = 16, z = 38, BA = 8, k = 51, z = 3.94, cluster-level pFWE-corr = .065, height threshold <0.001).

To summarize the results for set-inclusion arguments, the higher the parental education, the higher was reliance on verbal regions, specifically left IFG. In addition, for children at the lower end of the parental education continuum, higher nonverbal skills were associated with greater reliance on left SPL and occipital areas, left and right precuneus, and right MFG, as compared with children at the higher end of the parental education continuum.

6.3 | Linear-order arguments: Role of parental education, verbal and nonverbal skill and their interaction

6.3.1 | Main effects of task

First, we identified brain regions involved in processing of linear-order arguments. At the whole brain level, linear-order arguments activated a wide network including left MFG, STG, SPL, SFG as well as right SPL, IPL, MTG, lingual, MFG (Figure 2).

6.3.2 | Parental education and verbal skill

First, we identified the brain regions that showed an increase or a decrease in activity during the evaluation of linear-order arguments with respect to parental education, verbal skill and their interaction across subjects using the contrast of (linear-order—baseline). Following the whole brain analysis, we used a small volume correction (SVC) procedure to examine activity within the ROIs (left IFG and bilateral SPL) using the same thresholds reported above.

No brain regions reached significance in terms of relations to parental education at the whole brain or within the ROIs. However, interactions with verbal skill reached significance. At the whole brain level, the interaction between parental education and verbal skill was negatively related to activation in one cluster in right MFG—the relation between verbal skill and activation in this cluster increased as
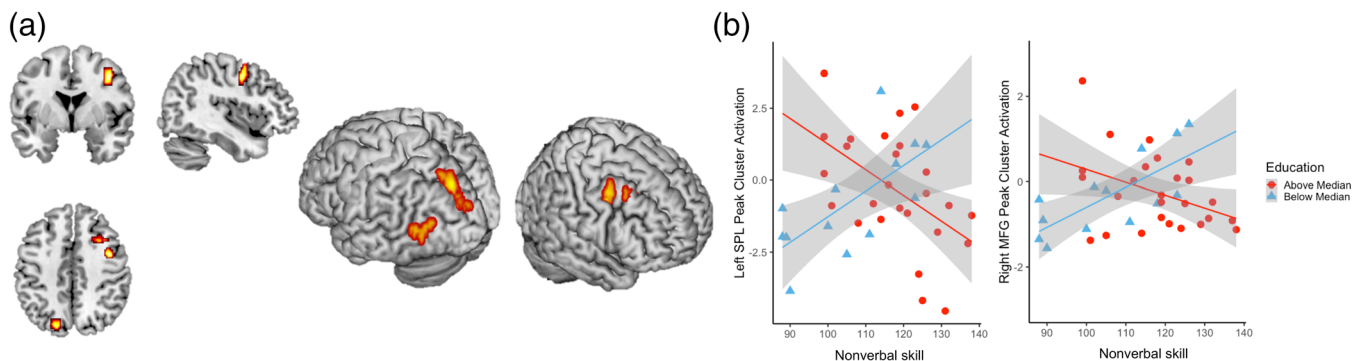

FIGURE 4 Interaction between parental education and nonverbal skill for set-inclusion problems. (a) Activity in left SPL/precuneus, left middle occipital, right precuneus and right MFG showed a parental education and nonverbal skill interaction. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI normalized anatomical brain (x = 62, y = 42, z = 2). (b) Eigenvariates was extracted from the peak of significant clusters in left SPL (x = −18, y = −78, z = 42) and right MFG (x = 28, y = 16, z = 38), and plotted against nonverbal skill scores for children above the median parental education (red) and below the median parental education (blue) for visualization purposes only
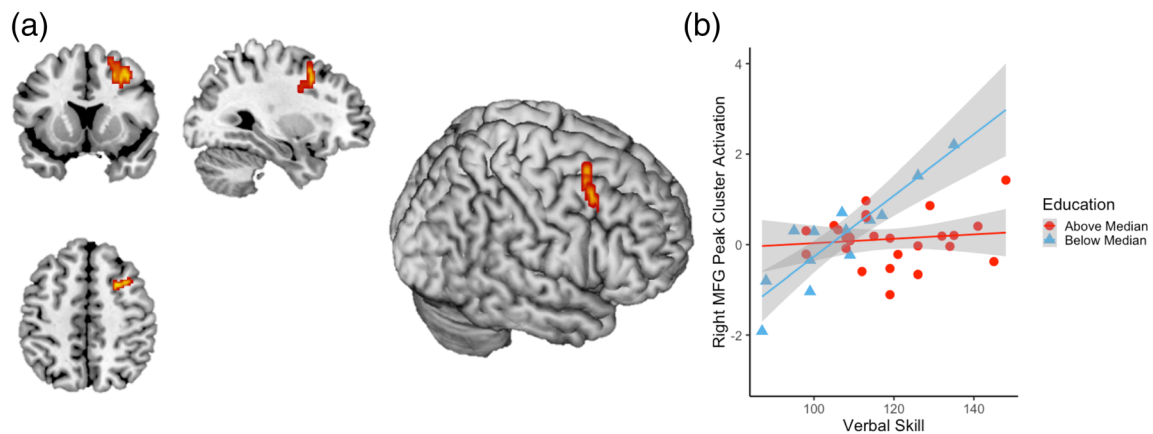
FIGURE 5 Interaction between parental education and verbal skill for linear-order problems. (a) Activity in right MFG showed a parental education and verbal skill interaction. Activation is overlaid on a 3D rendering and on coronal, sagittal, and axial slices of MNI normalized anatomical brain. (b) Eigenvariates was extracted from the peak significant cluster in right MFG (x = 26, y = 12, z = 46), and plotted against verbal skill scores for children above the median parental education (red) and below the median parental education (blue) for visualization purposes only

parental education decreased (see Table 3). To examine the overlap between this right MFG cluster and the right MFG cluster observed in set-inclusion processing analysis, we intersected the two maps using ImCalc tool of SPM. Indeed, the right MFG cluster found in this analysis overlapped with the activation in right MFG which correlated with nonverbal skill in set-inclusion problems (x = 30, y = 14, z = 42, BA = 8, k = 5, z = 3.68, cluster-level pFWE-corr = .05, height threshold <.001). No additional activation was observed within the ROIs.

To better characterize the interaction, for visualization purposes only, we divided the children into two groups based on median education, 16 years (lower than or at the median constituting lower parental education, and higher than the median constituting higher parental education). We then extracted the eigenvariate from the significant cluster described above and plotted it against verbal skill for the two parental education groups. This plot showed that for children below the median on parental education, verbal skills appears to be positively associated with activity in right MFG, but there seems to be no relation for children with above-median parental education (see Figure 5).

Last, to test the specificity of the association, we ran an additional model where we included nonverbal skill in addition to verbal skill in the model. In this model, even after controlling for general nonverbal skill differences, the interaction between parental education and verbal skill was negatively related to activation in right MFG (x = 26, y = 10, z = 42, BA = 8, z = 4.20, k = 76, cluster-level pFWE-corr = .026, height threshold $p < .001$).

6.3.3 | Parental education and nonverbal skill

Second, we ran an identical model using nonverbal skill instead of verbal. At the whole brain level or within the ROIs, no brain regions reached significant in terms of relations to parental educations or interactions with nonverbal skill.

To summarize, for linear-order arguments, there was no main effect of parental education. However, for children at the lower end

of the parental education continuum, higher verbal skills were associated with greater reliance on right MFG, as compared with children at the higher end of the parental education continuum.

7 | DISCUSSION

The goal of the current study was to ask how the neurocognitive basis of deductive reasoning differs along the parental education continuum. We examined children's processing of set-inclusion vs. linear-order relations, which are proposed to rely more on verbal and spatial processes, respectively. Our results showed that the neurocognitive basis of deductive reasoning as well as brain-behavior relations varied as a function of parental education. Confirming our predictions, higher parental education was correlated with greater activity in left IFG during the processing of set-inclusion relations, suggesting greater engagement of verbal mechanisms, but this did not differ by skill as predicted. Parental education was not related to activation during linear-order relations, perhaps because of the smaller SES effects on nonverbal processing (Avants et al., 2015). As expected, children at the lower end of the parental education continuum who were higher skill engaged the left parietal areas for set-inclusion problems. This is consistent with work suggesting that lower SES children show adaptations and engage spatial mechanisms to a greater degree (Demir et al., 2015). Children with lower parental education and who were higher skill engaged the right MFG to a greater degree for both set-inclusion and linear-order relations, suggesting greater engagement of cognitive control mechanisms.

7.1 | Parental education correlates with verbal neurocognitive systems that underlie reasoning

Consistent with our predictions, activation in a region of left IFG positively correlated with parental education for set-inclusion

relations—the higher the parental education the higher was the activation in left IFG. The correlation with parental education was specific to set-inclusion relations and was not observed for linear-argument relations. The finding that set-inclusion relation processing is related to activation in verbal regions is consistent with the prior literature. Both verbal and spatial representations can underlie deductive reasoning, but their engagement depends upon the structure of the argument (Prado et al., 2013). Set-inclusion relations involve Aristotelian quantifiers (e.g., "all," "some"). Such set-inclusion relations are frequently compatible with multiple spatial representations; a set-inclusion relation such as *"All larns are white"* could indicate the identity or the inclusion of two sets. Statements that are compatible with more than one model are easier to encode with verbal forms, compared with spatial forms. Thus, set-inclusion arguments might not be as conducive to eliciting visuospatial images as linear-order, and might more heavily rely on verbal skills (Prado et al., 2010; Prado et al., 2011, 2013). Indeed, processing of set-inclusion relations is preferentially associated with activation in verbal areas (e.g., left IFG), whereas processing of linear-order relations is associated with activation spatial areas (e.g., SPL and precuneus) in both adults and in children (Mathieu et al., 2015). Differential activation in verbal and spatial regions might be due to a multitude of reasons, ranging from the lexical content of the arguments to the ease of creating a visual–spatial image to represent the relation (e.g., Coventry et al., 2013; Noordzij et al., 2008; Knauff & Johnson-Laird, 2002; Wallentin et al., 2005). It is important to note that our observed relations were centered on BA46, which plays a significant role in verbal working memory. In processing set-inclusion relations, the left IFG activation might be necessary to retrieve isolated propositional representations and combine them in a step-by-step manner (Favrel & Barrouillet 2000). Overall, children with higher parental education might recruit verbal regions, specifically the left IFG, to a greater extent when processing set-inclusion relations than their peers from disadvantaged backgrounds.

We add to the literature by revealing that the neurocognitive representations underlying reasoning vary not only as a function of the reasoning type, but also as a function of individual differences in environmental experiences—specifically parental socioeconomic status. This finding is consistent with our prediction and prior work that showing significant and pronounced SES-related differences in verbal processing (e.g., Demir et al., 2015; Noble, Norman, & Farah, 2005). Previous neuroimaging studies suggest that the neural basis of verbal processing, specifically the left IFG, is more specialized in higher SES children (Hackman & Farah, 2009; Raizada et al., 2008; Younger et al., 2019). During development children from advantaged SES backgrounds might have learned to better manipulate verbal representations compared with children from relatively disadvantaged backgrounds. Being able to manipulate verbal representations more easily might aid higher SES children when processing set-inclusion relations—for example in storing arguments as isolated propositional representations and coordinating them in a step-by-step manner to derive conclusions.

Children's early experiences might account for the observed differences underlying reasoning. The neural dissociation between set-

inclusion and linear-order arguments are present in children as young as 8 years of age and do not vary by age during school years (Mathieu et al., 2015). Thus, differences might emerge before the period of elementary education. A significant aspect of children's early experiences that predicts children's verbal skills is the verbal input parents provide. Children widely differ from each other along the SES continuum in their exposure to verbal input (Hart & Risley, 1995; Hoff, 2003; Rowe, 2008). Early parental language input might account for why reliance SES relates to ease in manipulating verbal representations and greater reliance on verbal neural systems during processing of set-inclusion relations. A recent neuroimaging study showed that children who experience richer parental verbal input exhibit greater activation in left IFG, independent of other possible confounders such as SES or IQ (Romeo et al., 2018). Parents with higher SES more frequently engage in conversations that involve higher-order reasoning, such as inferences, abstractions, with their children. They also begin having these conversations earlier in life, as early as child age 2, compared with parents from more disadvantaged backgrounds (Frausel et al., 2020). Therefore, children's early experiences with language input might have better familiarized them with verbal representations which children might more easily manipulate when solving set-inclusion problems.

We had predicted that high verbal skill should be associated with more robust engagement of verbal regions, particularly for higher SES as we did in our prior studies. Contrary to our expectations, we did not observe this. Instead, we observed a main effect of parental education. Null results are hard to interpret because the current study may be underpowered to detect interaction effects, but the lack of an interaction might be because by the time children reach school settings, children with higher parental education might have received necessary verbal support to successfully process set-inclusion problems. Verbal enrichment accompanied by high parental education might buffer the role low verbal skills in reasoning problems that are typically verbally presented among children with higher parental education. Indeed, prior work with younger children similarly showed that high SES might buffer against the effects of low verbal skill (Noble, Farah, & McCandliss, 2006).

7.2 | Parental SES moderates the relations between reasoning skill and spatial neurocognitive systems that underlie reasoning

We did not observe main effects of parental education on the brain basis of set-inclusion or relational-order processing. Instead, we observed that parental education moderates the relation between nonverbal skill and the activation in spatial neurocognitive systems that underlie set-inclusion processing, specifically parieto-occipital areas, including SPL and precuneus. Before we elaborate on these results, we would like to emphasize that due to our small sample size, the interaction analyses should be considered as exploratory analyses. For children at the lower end of the parental education continuum, higher nonverbal skill was correlated with greater activation in

parieto-occipital areas compared with children at the higher end of the parental education continuum. These parieto-occipital areas are typically recruited for reasoning problems that rely on spatial visualization. Although set-inclusion arguments typically rely on verbal representations (Goel, Buchel, Frith, & Dolan, 2000; Prado et al., 2011, 2013), that does not mean that spatial representations can never be used when reasoning with set-inclusion relations. For example, prior work showed that gifted adolescents recruit a wider network in bilateral precuneus and occipital areas when solving reasoning tasks (Desco et al., 2011). In the relative absence of the history of rich verbal input that children with higher parental education receive, children with lower parental education might instead rely on spatial strategies when reasoning about set-inclusion relations to a greater extent than their peers. This might particularly be the case for children who have higher nonverbal skills. Reliance on visuospatial networks during reasoning is in line with our prior work. Prior we showed that for children from lower SES backgrounds, higher math skill is associated with greater reliance on visuospatial networks when solving single-digit arithmetic problems (Demir et al., 2015), reliance on visuospatial networks predicts greater math skill growth for lower SES children (Demir-Lira et al., 2016), and higher reading skill is associated with higher white matter integrity in tracts associated with visuospatial processing (Gullick et al., 2016). It is important to note although we consider activation in the aforementioned areas to evidence use of nonverbal strategies, it is possible that these regions carry different functions for children along the SES continuum. Future work with child-level localizers of language would strengthen our argument. Taken together, children who come from disadvantaged backgrounds might reveal adaptations and recruit different systems in the brain to perform on par with their peers.

7.3 | Parental SES moderates the relations between reasoning skill and prefrontal systems that underlie cognitive control

Our third main finding was that parental education moderates the relation between behavioral skill and the activation in prefrontal systems that underlie reasoning—specifically in right middle frontal gyrus (BA 6/8). When solving set-inclusion problems, children who are at the lower end of the parental education continuum and have higher nonverbal skills have higher activation in right MFG than their peers from advantaged backgrounds. When solving linear-order problems, children who are at the lower end of the parental education continuum and have higher verbal skills, had higher activation in same region as compared with their peers from advantaged backgrounds. These results suggest that children who have better nonverbal skills might manipulate visuospatial representations to solve set-inclusion problems, although these are typically represented by verbal systems. Children who have better verbal skills might manipulate verbal representations to solve linear-order problems, although these are typically represented by visuospatial systems. Overall, we argue that greater reliance on the middle frontal gyrus might be an indication of

children with lower parental education experiencing higher task demands in attempting to recruit an alternative network for a task. Supporting this view, hyperactivation in right-lateralized frontal systems has been interpreted as a compensatory process to overcome possible dysfunctions in the posterior areas in children with dyslexia (Hoeft, Patael et al. 2018; Shaywitz et al., 2002). Further, the right middle frontal gyrus is instrumental in cognitive control and is activated in a diverse set of executive function tasks, such as working memory or attention shifting (Bunge, Dudukovic, Thomason, Vaidya, & Gabrieli, 2002; Dosenbach, Fair, et al., 2007; Smith & Jonides, 1999).

It is important to note we report parental education-related differences in BA 6/8 whereas middle frontal areas specific to reasoning processes frequently observed in neuroimaging studies of reasoning are more rostral, typically in BA 10 (Prado et al., 2011). The only prior study on the structural brain differences related reasoning as a function of SES similarly reported that bilateral thickness of rostral middle frontal gyrus was differentially related to reasoning as a function of SES (Leonard et al., 2019). In summary, our results showed that children with lower parental education who were higher skill might rely on frontal systems associated with cognitive control, such as the right MFG, to a greater degree for both set-inclusion and linear-order relations to perform on par with their peers from more advantaged backgrounds.

The current study has several limitations that should be addressed in future studies. One limitation of the present study is our findings are correlational and we cannot comment on the direction of influence. Second, our sample had a rather restricted range of parental education, where we did not have subjects from the lowest end to the education continuum. This homogeneity allowed us to examine parental education-related differences without SES related differences in behavioral measures, which could confound neural effects with differences due to accuracy or motivation. In addition, SES-related differences in brain structure and function is observed across the entire SES spectrum (Noble et al., 2015). We used parental education as our measure of SES, since parental education is considered the strongest predictor of academic achievement. Recent efforts emphasize the need to use a consistent and comprehensive measure of SES (Pollak & Wolfe, 2020), and our results should also be confirmed using a wider range of SES indicators, including income and occupation. Using a less restricted and a more comprehensive SES measure might lead to stronger effects than the ones observed in the current study. Further, task-related pediatric imaging is challenging and our sample size remains limited. Given previous reports suggesting that the replicability of brain-behavior correlations with fMRI may require large sample sizes (Marek et al., 2020; Yarkoni & Braver, 2010), our study might be underpowered. Thus, our results, especially the ones focusing on the interaction between SES and skill, should be considered exploratory and should be replicated in larger samples. We also did not have direct measures of children's proximal environment—specifically the language input they receive at home. Given recent work showing that proximal parental language input might explain the SES-related differences in the brain, future studies attempting to unpack the intermediate mechanisms that underlie SES-related differences in reasoning

should similarly integrate children's day to day proximal interactions. Finally, the in-scanner reasoning tasks we used were highly verbal. For example, one could have expected individual differences in reading performance to influence children's processing of the arguments. Our preliminary analysis did not reveal any significant correlations (all p's > .10) between children's accuracy and reaction time on the reasoning problems and their reading skills (as measured by Woodcock-Johnson Word Attack, Letter-word Identification, and Passage Comprehension subtests). However, future work also including nonverbal stimuli will be beneficial in separating reasoning processes from language processing.

Overall, we extend the prior literature on SES-related differences on the neurocognitive systems by focusing on reasoning skills. Academically-relevant skills can be divided into constrained versus unconstrained skills. Constrained skills are finite skills with a ceiling wherein most children achieve perfect performance, such as reading single words or memorizing arithmetic facts (Snow & Matthews, 2016). Unconstrained skills are limitless, have a more extended developmental trajectory, and determine school success in later years. In contrast to constrained skills which are easily teachable via direct teaching, unconstrained skills are acquired gradually through experience and have been difficult to target via classroom teaching. A central example of unconstrained skills is reasoning and problem solving (McCormick et al., 2020; Snow & Matthews, 2016). Given the prior findings emphasizing the difficulty in training unconstrained skills, neuroimaging studies could reveal important information about the variability in children's responses to instruction. We show that children who come from disadvantaged backgrounds might recruit different systems in the brain even in the absence of behavioral differences. While the majority of the intervention efforts take a one-size-fits-all approach, our results suggest that even in the absence of skill differences, children might recruit different systems. Interventions leveraging children's existing strategies might meet with greater success. Future work should examine whether, for example, children who come from disadvantaged backgrounds, might benefit from an intervention that includes visuospatial supports, such as manipulatives or gestures (Cook & Goldin-Meadow, 2006; Richland & McDonough, 2010).

To summarize, to our knowledge, this is the first study to examine relations between parental SES, measured by parental education in the current study, and the functional neurocognitive systems underlying reasoning. First, we show that parental education is associated with greater reliance on verbal systems when solving reasoning problems that typically rely on verbal systems in the brain. Second, we also show that parental education moderates brain-behavior relations. We see that children who are at the lower end of the parental education continuum, but have higher nonverbal skills rely to visuospatial mechanisms in the parietal areas to a greater degree than their peers for solving set-inclusion problems. We also find that children with lower parent who are higher skill engage cognitive control mechanisms in the frontal regions to a greater degree for both set-inclusion and linear-order relations to achieve parity with their peers from advantaged backgrounds. Overall, our study shows that children from who from disadvantaged backgrounds

might recruit spatial and cognitive control networks to perform on par with peers. Better understanding variability in the neurocognitive networks children recruit as a function of their parental background might benefit future individualized interventions that best match children's characteristics.

CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on OpenNeuro.org.

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