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The Relationship Between Maternal Education and the Neural Substrates of Phoneme Perception in Children: Interactions Between Socioeconomic Status and Proficiency Level

Lisa L. Conant^a, Einat Liebenthal^{a,b}, Anjali Desai^a, and Jeffrey R. Binder^a

^aDepartment of Neurology, Medical College of Wisconsin, Milwaukee, WI, USA

^bDepartment of Psychiatry, Brigham and Women's Hospital, Harvard Medical School, Boston, MA, USA

Abstract

Relationships between maternal education (ME) and both behavioral performances and brain activation during the discrimination of phonemic and nonphonemic sounds were examined using fMRI in children with different levels of phoneme categorization proficiency (CP). Significant relationships were found between ME and intellectual functioning and vocabulary, with a trend for phonological awareness. A significant interaction between CP and ME was seen for nonverbal reasoning abilities. In addition, fMRI analyses revealed a significant interaction between CP and ME for phonemic discrimination in left prefrontal cortex. Thus, ME was associated with differential patterns of both neuropsychological performance and brain activation contingent on the level of CP. These results highlight the importance of examining SES effects at different proficiency levels. The pattern of results may suggest the presence of neurobiological differences in the children with low CP that affect the nature of relationships with ME.

Keywords

fMRI; speech perception; phoneme perception; socioeconomic status; child development

1. Introduction

Family socioeconomic status (SES) is associated with many aspects of child health and development, with continued effects seen into adolescence and adulthood. Numerous studies have shown a relationship between SES and neuropsychological functioning, particularly in the domains of language and executive functions (Ardila, Rosselli, Matute, & Guajardo, 2005; Hackman & Farah, 2009; Hackman, Farah, & Meaney, 2010; Noble, McCandliss, & Farah, 2007; Noble, Norman, & Farah, 2005). In addition, relationships between SES and

Correspondence: Dr. Lisa L. Conant, Department of Neurology, Medical College of Wisconsin, 9200 W. Wisconsin Ave., Milwaukee, Wisconsin 53226, USA, Phone: (414) 805-5276, Fax: (414) 259-9012, lconant@mcw.edu.

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both brain structure and function have been reported (Hanson et al., 2013; Jednoróg et al., 2012; Kishiyama, Boyce, Jimenez, Perry, & Knight, 2009; Krishnadas et al., 2013; Noble, Houston, Kan, & Sowell, 2012; Otero, 1997; Otero, Pliego-Rivero, Fernandez, & Ricardo, 2003; Raizada, Richards, Meltzoff, & Kuhl, 2008; Sheridan, Sarsour, Jutte, D'Esposito, & Boyce, 2012; Tomarken, Dichter, Garber, & Simien, 2004). Importantly, brain and behavioral differences do not always co-occur, as SES-related differences in neural responses associated with specific cognitive functions such as auditory selective attention have also been found in the absence of any differences in behavioral performance (D'Angiulli, Herdman, Stapells, & Hertzman, 2008; Stevens, Lauinger, & Neville, 2009).

Family SES is typically operationalized using parental education, occupation, or income, either individually or in some combination. Studies examining composite measures of SES and the different components have suggested that maternal education (ME) may be an optimal choice for predicting at least some outcomes including language development, reading, or educational attainment (Fluss et al., 2009; Raviv et al., 2004; Bradley and Corwyn, 2003; Haveman and Wolfe, 1995). This may be due to its strong associations with multiple parenting behaviors (Augustine, Cavanagh, & Crosnoe, 2009; Bornstein, Hahn, Suwalsky, & Haynes, 2003; Callahan & Eyberg, 2010) many of which have been found to mediate the relationships between SES and child development, such as cognitive stimulation in the environment (Raviv et al., 2004), expectations (Davis-Kean, 2005), selection of academically advantageous early child-care arrangements (Augustine et al., 2009), knowledge about child development, and quantity and quality of child-directed speech (Rowe, 2008).

The latter may be particularly important for language given that the language environment is known to play an important role in shaping language development even before birth. Newborns tested within 75 hours of birth can already distinguish between native and non-native vowel sounds (Moon, Lagercrantz, & Kuhl, 2013), although they are initially able to discriminate contrasts that are phonemic in languages to which they have had no exposure. This sensitivity to non-native phoneme contrasts begins to decline in the latter part of the first year of life (Cheour et al., 1998; Eimas, 1975; Werker & Tees, 1984), while categorical perception of native phonemes becomes stronger. Categorical perception (CP) refers to greater sensitivity to acoustic variations that cue phonemic categories than to acoustic variations of a similar extent within a phonemic category. The ability to disregard phonemically irrelevant acoustic variability is necessary in order to recognize a wide variety of physically different sounds as exemplars of the same phoneme, which is important given that repeated utterances of the same phoneme vary acoustically both within and across speakers. CP of native phonemes is an important component of language development, as evidenced by the strong relationship between infant phoneme perception and later language abilities (Kuhl et al., 2008), as well as findings implicating CP deficits in at least some cases of specific language impairment (Joanisse & Seidenberg, 1998; Ziegler, Pech-Georgel, George, & Lorenzi, 2011) and dyslexia (Noordenbos & Serniclaes, 2015). This ability continues to develop between the ages of 6 and 12 years, with performance still not reaching adult levels at the upper end of this age range (Bogliotti, 2003; Elliott, Longinotti, Meyer, Raz, & Zucker, 1981; Hazan & Barrett, 2000).

To our knowledge, the relationship between CP of phonemes and ME has only been directly examined in infants in the first year of life, and this work failed to find an association (Liu, Kuhl, & Tsao, 2003; Tsao, Liu, & Kuhl, 2004), although an effect of the quality of maternal vowel clarity on phoneme perception was found (Liu et al., 2003). The failure to find a relationship at this age is consistent with other studies looking at the relationship between parental education and different aspects of cognitive functioning, which have similarly suggested that behavioral differences may not be evident or are variable in the first year to two of life (Mayes and Bornstein, 1995; Roberts and Bornstein, 1999; Tsao et al., 2004). An increasingly strong relationship between ME and language functioning has been found from two to four years of age (Reilly et al., 2010), and Noble et al. (2012) found greater parental-education-related differences in brain volume associated with increasing age in the left inferior frontal and superior temporal gyri in a sample of children and adolescents ranging from 5 to 17 years of age. Thus, it is possible that ME may have an effect on CP and potentially its neural substrates at later ages.

Two neurophysiology studies have linked ME to aspects of auditory processing that could affect the development of phoneme perception. Using an event-related potential measure of selective auditory attention in children aged 3 to 8 years, Stevens et al. (2009a) reported that children of mothers with no college experience showed reduced ability to suppress responses to irrelevant information relative to those with higher ME levels. In a study by Skoe et al. (2013) examining auditory brainstem responses, adolescents with mothers who had lower educational levels demonstrated less consistent neural responses to speech over repeated stimulation, weaker encoding of speech-specific information, and greater activity in the absence of auditory stimulation compared to participants with higher ME levels. Both of these studies suggest that lower levels of ME may be associated with noisier, less efficient processing of auditory stimuli including speech sounds.

We previously used fMRI to examine the neural substrates associated with CP in 7- to 12-year-old children as well as the relationships among level of CP proficiency, associated activation patterns, and the development of reading and phonological processing abilities (Conant, Liebenthal, Desai, & Binder, 2014). While multiple regions in left frontal, temporal, and parietal cortex were activated more for phonemic sounds relative to nonphonemic sounds matched for spectrotemporal complexity, the extent of left lateralization in posterior temporal and parietal regions differed depending on the level of phoneme categorization ability. Specifically, regions of interest analyses revealed that children exhibiting strongly categorical phoneme perception showed left lateralization in these two regions for the phonemic sounds, whereas those with lower categorical proficiency showed right lateralization. In contrast, the proficient categorizing group showed right lateralized activation in these areas for the nonphonemic sounds, while the low CP group showed more bilateral or weak left lateralization. CP proficiency was also found to be strongly related to activation in the left ventral occipitotemporal cortex, an area frequently associated with orthographic processing.

In the current study, we examined the relationships between ME and brain activation during phonemic and nonphonemic discrimination tasks and between ME and performance on measures of intellectual functioning, reading, and phonological processing in the same

sample of children, while taking into account CP proficiency level. We hypothesized that higher levels of ME would be positively correlated with performance on the neuropsychological variables, particularly those assessing verbal abilities, and with increased activation associated with the tasks. We expected stronger relationships in children with lower CP given that other studies have found greater effects of SES in at-risk groups (e.g., Monzalvo et al., 2012; Tomarken et al., 2004). The location of increased activation could be either in areas subserving CP or in areas not typically recruited for this task, with the latter suggesting compensatory activation.

2. Methods

2.1 Participants

Participants in the fMRI study were 39 monolingual, right-handed children, 7 to 12 years of age, who had no history of significant neurological illness or injury, hearing impairment, developmental speech, language or learning disorder, chronic medical illness, or psychiatric disorder. Participants as well as at least one of their parents were native speakers of American English. The latter was necessary to ensure that the children were exposed to American English phonemes from birth. Children were excluded if they had fewer than 40 trials remaining in the phonemic (P) or the nonphonemic (N) scanner conditions after removal of trials in which no response was given or excessive movement occurred. Application of this criterion resulted in the exclusion of 6 children. One additional child was excluded due to poor image quality, leaving a final sample of 32 children (Age: Mean (SD) = 10.30 (1.54)). The study protocol was approved by the relevant Institutional Review Board. Parents of all participants gave written informed consent, and children provided written assent.

Based on parent report, none of the children spoke another language fluently, but most (75%) were reported to have some limited knowledge of one or more languages other than English. In this regard, 53.1% were reported to have some knowledge of one other language, while 15.6% and 6.3% had some exposure to two or three additional languages, respectively. In addition, 56.5% played a musical instrument, with varying ranges of experience (0.5 to 4 years, mean = 2.4 years) and rated proficiency (1 (novice)-5 (virtuoso), mean = 2.6).

Maternal education was assigned a numerical value based on the number of years of education generally associated with the highest level of education achieved. These values were as follows: high school degree = 12; some college, no degree = 13, Associate's degree = 14; Bachelor's degree = 16; some graduate school, no degree = 17; Master's degree = 18; and professional degree (Ph.D. or M.D.) = 20. No mother had less than a high school education.

2.2 Stimuli

Stimuli were created using a cascade/parallel formant synthesizer (SenSyn Laboratory Speech Synthesizer, Sensimetrics Corp., Cambridge, MA). The P items consisted of a 7-token continuum from /ba/ to /da/. The anchor points of the N continuum were constructed by spectrally inverting the first formant of the speech syllables in order to disrupt their

phonemic value without altering their general spectrotemporal characteristics. The details regarding these stimuli are provided in Conant et al. (2014).

2.3 Procedure

Participants completed a brief audiometric screening test to ensure that they had no significant hearing impairment. Brief neuropsychological testing was also conducted, which included measures of estimated IQ (the Wechsler Abbreviated Scale of Intelligence [Wechsler, 1999]) - Vocabulary and Matrix Reasoning subtests), single-word reading (Wide Range Achievement Test-3rd Edition [Wilkinson, 1993]- Reading subtest), and phonological processing (two subtests of the Comprehensive Test of Phonological Processing [Wagner et al., 1999]). With regard to the latter, the aspects of phonological processing assessed included phonological awareness (Elision) and the rapid retrieval of phonological codes associated with letter stimuli (Rapid Letter Naming).

During scanning, participants performed a same-different (AX) discrimination task. The distance in acoustic space between the tokens in each pair was identical, but, for the P items, one token-pair is within the /ba/ category (1–3), one is within the /da/ category (5–7), and one crosses the phonemic category boundary (3–5). Each run contained ten discrimination pairs of each type and five baseline silence trials. Participants completed four to six runs. As a measure of categorical discrimination performance, a phonemic Categorical Perception Index (CPI) was computed. This index was defined as the difference between the percentage of across-category P pairs perceived as “different” and the average percentage across the two sets of within-category P pairs perceived as “different”. Additional details can be found in Conant et al. (2014).

2.4 Image Acquisition

Images were acquired on a 3T GE Signa Excite scanner (GE Medical Systems, Milwaukee, WI). Whole-brain fMRI data were acquired using gradient-echo, echoplanar imaging (TE = 20 ms, flip angle = 90°) at long intervals (TR=7 s; acquisition time=2 s). The clustered acquisition paradigm was used to avoid perceptual masking of the test items and to lessen the contamination of the BOLD data by the acoustic noise of the scanner (Edmister, Talavage, Ledden, & Weisskoff, 1999). A single trial, including presentation of the pair of stimuli and acquisition of the participant’s response, occurred in the interval between image acquisitions. Thirty-six axial slices, 3 mm thick, were acquired with 0.5 mm gap between slices to prevent signal bleed. The field of view was 220 cm and matrix 64×64, resulting in nearly isotropic 3.44-mm voxels covering the whole brain. High resolution, T1-weighted structural images were obtained at each session using a 3D SPGR sequence (TE = 3.9 ms, TR = 9.5 ms, TI = 450 ms, flip angle = 12°, matrix = 256 × 224, NEX = 1, slice thickness 1.2 mm, 106 axial slices, scan time = 6.23 min).

2.5 Image Analysis

Image processing and statistical analysis were performed using the Analysis of Functional Neuroimages (AFNI) software package (Cox, 1996). Within-subject analysis included volumetric image registration to minimize head motion artifacts, smoothing with a 6mm FWHM Gaussian filter, and voxelwise multiple linear regression with reference functions

representing experimental conditions (P, N) and regressors of no interest (linear and nonlinear trends, condition-specific RTs, and motion parameters). Deconvolution analysis was performed to allow the hemodynamic response function to vary across voxels and stimulus conditions. Missed trials (i.e., trials on which the participant did not respond) and trials with greater than 10% outlier voxels (an index of excessive motion) were removed from the analyses. Individual t-maps were computed to determine the significance of the activation (relative to rest) in each of the experimental conditions. General linear tests were conducted for each contrast. Individual anatomical scans and statistical t-maps were transformed into standard stereotaxic space (Talairach & Tournoux, 1988).

Activation maps were generated using random effects analysis. The relationship between ME and activation was first examined using a simultaneous multiple linear regression analysis in the full sample with the following regressors: the mean-centered variables of age, CPI scores, and ME, as well as a $\text{CPI} \times \text{ME}$ interaction term, with the latter two being the regressors of interest in the current paper. The contrast maps were thresholded at a voxelwise $|z| > 2.327$, and clusters smaller than 11874 μl were removed to yield a mapwise threshold of $\alpha < 0.05$ based on Monte Carlo simulations. Recent work has shown that the spatial autocorrelation function of fMRI noise does not follow a Gaussian shape, but rather has heavier tails (Eklund, Nichols, & Knutsson, 2016). Therefore, for these simulations, a spatial autocorrelation function of a mixed Gaussian plus mono-exponential form, which has longer tails than the Gaussian model, was used to generate the noise random fields. Once the areas showing significant interactions were identified, the regression model without the interaction term was re-run in order to examine whether there were unconditional main effects of ME in areas in which no significant interaction effect was found.

To elucidate the nature of a significant interaction effect in a given contrast, a mask was created including only the voxels that showed the interaction effect. The mask was applied to the individual contrast maps of each participant for that contrast (e.g., P relative to baseline), and the average beta coefficient within the region of the interaction effect was calculated. Rather than performing a median split, the sample was divided into two groups at the point in the distribution of CPI scores where there was a large discontinuity or gap in the scores, forming a Low CPI group (<50 ; $n = 9$) and a High CPI group (>60 ; $n = 23$). Dividing the sample at this point maximizes the differences between the two groups and precludes the comparison of two groups in which at least some of the participants in both groups performed highly similarly. It also results in two groups with similarly sized ranges of CPI scores. The distribution of scores is graphically illustrated in Supplementary Figure 1. Regression analyses examining the relationship between ME and the average beta coefficients while controlling for age were performed in each CPI group. Group effects were only examined in those contrasts in which a significant interaction effect was found. A Benjamini-Hochberg false discovery rate (FDR) correction (Benjamini & Hochberg, 1995) was applied to these individual group analyses to adjust for multiple tests.

The Low and High CPI groups did not significantly differ with regard to age, sex, estimated IQ, single-word reading, phoneme deletion, rapid serial naming of letters, median response times (RTs) in P and N, percentage of P and N items on which there was no response, or percent of image volumes removed from P or N for motion (see Conant et al., 2014). There

were also no significant differences between groups for race ($p = .184$), ethnicity ($p > .9$), ME (Low CPI: Mean (SD) = 14.78 (2.28); High CPI Mean (SD) = 15.39 (2.71); $p = 0.666$), number exposed to another language (Low CPI: 67%; High CPI: 78%; $p = 0.654$), number who play a musical instrument (Low CPI: 22%; High CPI: 57%; $p = 0.122$), vocabulary knowledge (Low CPI: Mean (SD) = 58.78 (7.60); High CPI: Mean (SD) = 61.30 (7.44); $p = .476$), or nonverbal reasoning performance (Low CPI: Mean (SD) = 54.44 (6.64); High CPI: Mean (SD) = 57.09 (6.32); $p = .414$).

2.6 Behavioral Data Analysis

With regard to the behavioral variables, similar simultaneous multiple regression analyses were used for the dependent variables of estimated Full Scale IQ, Vocabulary, Matrix Reasoning, Reading, Elision, and Rapid Letter Naming. Age was not included as a regressor in these analyses because age-corrected standard scores were used for all measures ($ps > .5$), and there were no significant relationships between age and either CPI ($r = -.012$, $p = .946$) or ME ($r = .089$, $p = .627$). When a significant interaction was found, separate correlational analyses were conducted for the Low and High CPI groups in order to clarify the nature of the interaction effect, and these analyses were FDR corrected. When no significant interaction was found, regression analyses were run again with the interaction term removed from the model in order to examine the unconditional main effects of ME. An FDR correction was applied to the ME and CPIxME regressors for the final models to adjust for multiple tests.

3. Results

3.1 Behavioral Results

A significant CPI $\times$ ME interaction was only found for Matrix Reasoning (see Table 1). It accounted for 18.6% of the variance in Matrix Reasoning performance. Follow-up analyses in the Low and High CPI groups (see Figure 1) revealed a significant positive correlation in the Low CPI group ($r = .760$, corrected $p = .036$), but not in the High CPI group ($r = .131$, corrected $p = .552$).

The nonsignificant interaction terms were removed from the remaining regression models. A significant effect of ME was seen with regard to overall estimated IQ and Vocabulary, and a trend was observed for Elision, with ME uniquely accounting for 20.3%, 21.4%, and 12.6% of the variance in these variables, respectively (see Table 1 and Figure 2). The ME regressor was not significant for Reading or Rapid Letter Naming.

3.2 FMRI Results

Based on the results of the behavioral analysis, two regressors were added to control for the cognitive correlates of ME. Because Vocabulary and Matrix Reasoning comprise IQ and are thus highly correlated with it ($rs > .850$), only IQ and Elision were included as covariates. In the full sample, there were no regions showing a significant ME effect in any contrast. There was also no significant CPI $\times$ ME interaction effect seen in the N relative to baseline or the P relative to N contrast.

For P relative to baseline, a significant $\text{CPI} \times \text{ME}$ interaction was found in multiple regions within left prefrontal cortex (see Figure 3A and Table 2), including the left inferior, middle and superior frontal gyri and the anterior insula. The regression analysis examining the relationship between ME and the average beta values across the voxels within this interaction effect for each subject while controlling for age (see Figure 3C) revealed a significant positive effect in the Low CPI group ($\beta = 0.858$, corrected $p = .021$), but no significant effect was seen in the High CPI group ($\beta = -0.223$, corrected $p = .251$).

4. Discussion

4.1 Behavioral Findings

Consistent with hypotheses and previous literature (Hoff & Tian, 2005; Hoff, 2003; Noble et al., 2007, 2005; Raviv et al., 2004; Rowe, 2008, 2012), the full sample showed relationships between ME and estimated IQ as well as two measures of language functions, vocabulary knowledge and phonological awareness. A significant interaction was seen with regard to the one nonverbal task administered, reflecting a significant relationship between ME and nonverbal reasoning only in children with lower categorical speech perception.

4.2 fMRI Findings

For P, the $\text{CPI} \times \text{ME}$ interaction effect in left prefrontal and insular cortex appears to predominantly reflect a significantly stronger positive correlation between ME and activation in these regions in children with lower CP proficiency, with no significant relationship seen at the higher end of the continuum. These results suggest that, at the higher end of the phonemic CP continuum, additional maternal education does not enhance activation associated with phonemic perception. The left IFG and anterior insula correlations overlapped with the areas of significant activation in the Low CPI group for the P-N contrast seen in our previous study (Conant et al., 2014). Thus, primary regions that the Low CPI group activates specifically for the phonemic categorization task do appear to be modulated by ME; however, no correlations were seen in regions previously found to be specifically associated with stronger phonemic CP proficiency.

SES-related differences have frequently been seen in prefrontal cortex (Hanson et al., 2013; Jednoróg et al., 2012; Kishiyama et al., 2009; Noble et al., 2012; Otero et al., 2003; Otero, 1997; Raizada et al., 2008; Sheridan et al., 2012; Tomarken et al., 2004). Raizada et al. (2008) found SES to be related to left hemispheric specialization in the IFG during a phonological task (rhyming) in 5-year-old children. In that study, the differences were greatest in the pars triangularis and opercularis. Activation of the posterior IFG during phoneme categorization has also been reported (Conant et al., 2014; Lee, Turkeltaub, Granger, & Raizada, 2012; Myers, Blumstein, Walsh, & Eliassen, 2009). In the current study, there was significant ME-related activation in the left IFG in the Low CPI group, including the pars triangularis, but little IFG activation was seen posterior to the caudal bank of the anterior ascending limb of the lateral sulcus. A significant focus was also seen more anteriorly in the pars orbitalis, which is an area typically associated more with semantic retrieval (Binder, Desai, Graves, & Conant, 2009). It is possible that this group is not able to

recruit more posterior IFG, and this anterior activation represents a compensatory process that is enhanced in those with higher levels of ME.

In this regard, the left anterior insula, which also showed a significant relationship with ME in children with lower CP proficiency, is an area that was found to be hyperactivated during reading-related tasks in individuals with dyslexia in a recent meta-analysis, and this finding was interpreted as an effort to use articulatory information to assist with the task (Richlan, 2012; Richlan, Kronbichler, & Wimmer, 2009). In addition, recent fMRI studies have found the anterior insula/adjacent frontal operculum, particularly on the left, to be sensitive to stimulus complexity in speech production tasks, suggestive of a possible role in articulatory speech control (Ackermann & Riecker, 2010; Bohland & Guenther, 2006; Riecker, Brendel, Ziegler, Erb, & Ackermann, 2008). Several studies have also shown activation in the anterior insula and adjacent medial frontal operculum in association with tasks involving speech identification, particularly as identification becomes more difficult such as in degraded speech or under noisy conditions (Binder, Liebenthal, Possing, Medler, & Ward, 2004; Erb, Henry, Eisner, & Obleser, 2013; Vaden et al., 2013; Wild et al., 2012), but, in these studies, this region appears to subserve more domain-general attentional, decision-making, or cognitive control processes. Thus, the ME-related activation in this region as well as in the SFG/MFG, which has also been implicated in cognitive control (Chang, Yarkoni, Khaw, & Sanfey, 2013; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013), may reflect increasing recruitment of executive resources in children for whom speech discrimination may be more difficult. However, the insular activations associated with executive processes are typically bilateral, while both the ME-related activation seen in the P condition and the activation previously seen in this region in P-N are strongly left-lateralized, suggesting the possibility of a more speech-specific role in the current study.

Significant prefrontal cortex involvement has also been seen in association with performance of matrix reasoning tasks (Gray, Chabris, & Braver, 2003; Perfetti et al., 2009; Prabhakaran, Smith, Desmond, Glover, & Gabrieli, 1997). This is interesting given that the Low CPI group showed a positive correlation between ME and performance on a matrix reasoning task that was not seen in the High CPI group. It may be that performance on nonverbal, executive tasks and activation in the regions that support them are more plastic or more open to modulation by factors such as ME in the children with low phonemic categorization proficiency.

4.3 SES and At-Risk Groups

The finding that ME was associated with increased activation to a much greater extent at the lower end of the CP continuum is consistent with studies showing greater SES-related differences in clinical groups or groups that are considered to be at-risk in some regard. For example, Tomarken et al. (2004) reported increased resting left frontal EEG activity associated with SES in adolescents at high familial risk for depression but not in those at low risk. Similarly, a greater relationship between SES and neuroimaging findings in a clinical group was reported by Monzalvo et al. (2012) who examined activation during passive listening to native and foreign language sentences in children with and without dyslexia from low and high SES families. In the comparison of the high- and low-SES groups, they

reported activation primarily in right hemisphere regions, including areas more associated with cognitive control, in the combined speech conditions relative to baseline and the foreign language condition relative to baseline. When the groups were examined individually, these differences were only significant in the group with dyslexia, not in the group of non-impaired readers. Importantly, the areas found to differentiate the non-impaired readers and those with dyslexia were strikingly similar across SES groups, suggesting a core group of anomalies in dyslexia, which were not modulated by SES. Thus, SES appeared to have more of an effect in the group with dyslexia, and the effects were seen outside of the areas associated with native language processing. These results are similar to the finding in the current study that SES has more of an effect in those with lower CP proficiency, and these effects are not in the same areas as those previously found to be differentially associated with stronger CP proficiency. This pattern may reflect neurobiological differences in the at-risk group as they may be unable to recruit the same areas. Higher ME does appear to allow the recruitment of additional resources, but these appear to be insufficient to overcome the deficit. The lack of modulation at the higher end may be because those without a deficit in this area are able to engage the necessary areas and perform the task, with no additional resources needed.

4.4 Limitations

In the current study, there are some significant limitations, including the small sample size of the Low CPI group. Importantly, the interaction effects were seen in the full group, with the nature of them subsequently elucidated using the individual CPI groups. Another limitation of the current study is the restricted range of maternal education examined. Specifically, all mothers had at least completed high school. Thus, these results cannot be generalized to those with lower levels of ME. However, it is noteworthy that significant effects were still seen at mid to high levels of ME.

4.5 Conclusions and Future Directions

In conclusion, in elementary- and middle-school-age children, relationships were found between ME and both neuropsychological performance and brain activation patterns associated with phoneme discrimination; however, the nature of these relationships varied depending on the level of CP. In general, the results suggested less environmental modulation in those with higher CP proficiency. However, for children with CP difficulties, higher ME may allow them to recruit additional resources, specifically within left prefrontal cortex, when performing a CP task. This activation is not in regions previously found to be more active in the children with higher proficiency, supporting the hypothesis that the children with lower CP abilities are not able to recruit those areas, even with additional environmental supports or advantages. Some of the regions recruited are ones involved in other cognitive domains, such as executive functions. While the additional activation appears insufficient to compensate with regard to performance on the CP task, it is notable that stronger performance was seen in association with ME on the one nonverbal, problem-solving task. The differences in the behavioral and brain activation correlations with ME across ability levels may suggest the presence of neurobiological differences at the lower end of the CP continuum that not only constrain phoneme categorization performance and

related patterns of activation as indicated by our previous study, but also render some cognitive functions and regions more or less amenable to environmental modulation.

Overall, the results of this study support the importance of continued efforts to investigate how ME may interact with ability level in this and other cognitive areas, which can be used to inform intervention efforts in different populations in order to optimize benefits. Future studies using larger samples and a wider range of ME as well as longitudinal designs will be important to determine the reliability and generalizability of these findings and to elucidate the nature and potential mutability of the effects over time at different levels of CP and ME. It will also be important to collect additional information regarding the home environment during infancy and early childhood in order to better understand what factors may mediate the relationships with ME.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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References

- Ackermann H, Riecker A. The contribution(s) of the insula to speech production: a review of the clinical and functional imaging literature. *Brain Structure & Function*. 2010; 214(5–6):419–33. <http://doi.org/10.1007/s00429-010-0257-x>. [PubMed: 20512374]
- Ardila A, Rosselli M, Matute E, Guajardo S. The influence of the parents' educational level on the development of executive functions. *Developmental Neuropsychology*. 2005; 28(1):539–60. http://doi.org/10.1207/s15326942dn2801_5. [PubMed: 15992255]
- Augustine J, Cavanagh S, Crosnoe R. Maternal education, early child care and the reproduction of advantage. *Social Forces*. 2009; 88(1):1–29. <http://doi.org/10.1353/sof.0.0233.Maternal>.
- Benjamini Y, Hochberg Y. Controlling the false discovery rate: a practical and powerful approach to multiple testing. *Journal of the Royal Statistical Society. Series B (Methodological)*. 1995; 57:289–300.
- Binder JR, Desai RH, Graves WW, Conant LL. Where is the semantic system? A critical review and meta-analysis of 120 functional neuroimaging studies. *Cerebral Cortex*. 2009; 19(12):2767–96. <http://doi.org/10.1093/cercor/bhp055>. [PubMed: 19329570]
- Binder JR, Liebenthal E, Possing ET, Medler DA, Ward BD. Neural correlates of sensory and decision processes in auditory object identification. *Nature Neuroscience*. 2004; 7(3):295–301. <http://doi.org/10.1038/nn1198>. [PubMed: 14966525]
- Bogliotti, C. Relation between categorical perception of speech and reading acquisition. In: Sole, MJ, Recasens, D., Romero, J., editors. *Proceedings of the 15th Annual Congress of the International Phonetic Sciences*. Barcelona: Futurgraphic; 2003. p. 885–888.
- Bohland JW, Guenther FH. An fMRI investigation of syllable sequence production. *NeuroImage*. 2006; 32(2):821–41. <http://doi.org/10.1016/j.neuroimage.2006.04.173>. [PubMed: 16730195]
- Bornstein, MH., Hahn, C-S., Suwalsky, JTD., Haynes, OM. Socioeconomic status, parenting, and child development: the Hollingshead Four-Factor Index of Social Status and the Socioeconomic Index of Occupations. In: Bornstein, MH., Bradley, RH., editors. *Socioeconomic Status, Parenting, and Child Development*. Mahwah, NJ: Lawrence Erlbaum Associates; 2003. p. 29–82.

- Bradley, R., Corwyn, R. Age and ethnic variations in family process mediators of SES. In: Bornstein, M., Bradley, R., editors. *Socioeconomic Status, Parenting, and Child Development*. Mahwah, NJ: Lawrence Erlbaum Associates; 2003. p. 161-188.
- Callahan CL, Eyberg SM. Relations between parenting behavior and SES in a clinical sample: validity of SES measures. *Child & Family Behavior Therapy*. 2010; 32(2):125–138. <http://doi.org/10.1080/07317101003776456>.
- Chang LJ, Yarkoni T, Khaw MW, Sanfey AG. Decoding the role of the insula in human cognition: functional parcellation and large-scale reverse inference. *Cerebral Cortex*. 2013; 23(3):739–49. <http://doi.org/10.1093/cercor/bhs065>. [PubMed: 22437053]
- Cheour M, Ceponiene R, Lehtokoski A, Luuk A, Allik J, Alho K, Näätänen R. Development of language-specific phoneme representations in the infant brain. *Nature Neuroscience*. 1998; 1(5): 351–353. Retrieved from http://www.nature.com/neuro/journal/v1/n5/pubmed/nn0998_351.html. [PubMed: 10196522]
- Conant L, Liebenthal E, Desai A, Binder J. fMRI of phonemic perception and its relationship to reading development in elementary-to middle-school-age children. *NeuroImage*. 2014; 89:192–202. Retrieved from <http://www.sciencedirect.com/science/article/pii/S1053811913012044>. [PubMed: 24315840]
- Cox RW. AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research*. 1996; 29(3):162–73. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/8812068>. [PubMed: 8812068]
- D'Angiulli A, Herdman A, Stapells D, Hertzman C. Children's event-related potentials of auditory selective attention vary with their socioeconomic status. *Neuropsychology*. 2008; 22(3):293–300. <http://doi.org/10.1037/0894-4105.22.3.293>. [PubMed: 18444707]
- Davis-Kean PE. The influence of parent education and family income on child achievement: the indirect role of parental expectations and the home environment. *Journal of Family Psychology*. 2005; 19(2):294–304. <http://doi.org/10.1037/0893-3200.19.2.294>. [PubMed: 15982107]
- Edmister WB, Talavage TM, Ledden PJ, Weisskoff RM. Improved auditory cortex imaging using clustered volume acquisitions. *Human Brain Mapping*. 1999; 7(2):89–97. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/9950066>. [PubMed: 9950066]
- Eimas PD. Auditory and phonetic coding of the cues for speech: Discrimination of the [r-l] distinction by young infants. *Perception & Psychophysics*. 1975; 18(5):341–347. <http://doi.org/10.3758/BF03211210>.
- Eklund A, Nichols TE, Knutsson H. Cluster failure: Why fMRI inferences for spatial extent have inflated false-positive rates. *Proceedings of the National Academy of Sciences*. 2016; 113 <http://doi.org/10.1073/pnas.1602413113>.
- Elliott LL, Longinotti C, Meyer D, Raz I, Zucker K. Developmental differences in identifying and discriminating CV syllables. *The Journal of the Acoustical Society of America*. 1981; 70(3):669–77. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/7288030>. [PubMed: 7288030]
- Erb J, Henry MJ, Eisner F, Obleser J. The brain dynamics of rapid perceptual adaptation to adverse listening conditions. *Journal of Neuroscience*. 2013; 33(26):10688–97. <http://doi.org/10.1523/JNEUROSCI.4596-12.2013>. [PubMed: 23804092]
- Fernald A, Marchman VA, Weisleder A. SES differences in language processing skill and vocabulary are evident at 18 months. *Developmental Science*. 2013; 16(2):234–48. <http://doi.org/10.1111/desc.12019>. [PubMed: 23432833]
- Fluss J, Ziegler JC, Warszawski J, Ducot B, Richard G, Billard C. Poor reading in French elementary school: the interplay of cognitive, behavioral, and socioeconomic factors. *Journal of Developmental and Behavioral Pediatrics*. 2009; 30(3):206–16. <http://doi.org/10.1097/DBP.0b013e3181a7ed6c>. [PubMed: 19412126]
- Gray JR, Chabris CF, Braver TS. Neural mechanisms of general fluid intelligence. *Nature Neuroscience*. 2003; 6(3):316–322. <http://doi.org/10.1038/nn1014>. [PubMed: 12592404]
- Hackman D, Farah M. Socioeconomic status and the developing brain. *Trends in Cognitive Sciences*. 2009; 13(2):65–73. <http://doi.org/10.1016/j.tics.2008.11.003>. *Socioeconomic*. [PubMed: 19135405]

- Hackman D, Farah M, Meaney M. Socioeconomic status and the brain: mechanistic insights from human and animal research. *Nature Reviews Neuroscience*. 2010; 11(9):651–659. <http://doi.org/10.1038/nrn2897.Socioeconomic>. [PubMed: 20725096]
- Hanson JL, Hair N, Shen DG, Shi F, Gilmore JH, Wolfe BL, Pollak SD. Family poverty affects the rate of human infant brain growth. *PLoS ONE*. 2013; 8(12):e80954. <http://doi.org/10.1371/journal.pone.0080954>. [PubMed: 24349025]
- Haveman R, Wolfe B. The determinants of children's attainments: A review of methods and findings. *Journal of Economic Literature*. 1995; 33:1829–1878. Retrieved from <http://www.jstor.org/stable/2729315>.
- Hazan V, Barrett S. The development of phonemic categorization in children aged 6–12. *Journal of Phonetics*. 2000; 28:377–396.
- Hoff E. The specificity of environmental influence: socioeconomic status affects early vocabulary development via maternal speech. *Child Development*. 2003; 74(5):1368–78. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/14552403>. [PubMed: 14552403]
- Hoff E, Tian C. Socioeconomic status and cultural influences on language. *Journal of Communication Disorders*. 2005; 38(4):271–8. <http://doi.org/10.1016/j.jcomdis.2005.02.003>. [PubMed: 15862810]
- Jednoróg K, Altarelli I, Monzalvo K, Fluss J, Dubois J, Billard C, Ramus F. The influence of socioeconomic status on children's brain structure. *PLoS ONE*. 2012; 7(8):e42486. <http://doi.org/10.1371/journal.pone.0042486>. [PubMed: 22880000]
- Joanisse MF, Seidenberg MS. Specific language impairment: A deficit in grammar or processing? *Trends in Cognitive Sciences*. 1998; 2(7):240–247. [http://doi.org/10.1016/S1364-6613\(98\)01186-3](http://doi.org/10.1016/S1364-6613(98)01186-3). [PubMed: 21244922]
- Kishiyama MM, Boyce WT, Jimenez AM, Perry LM, Knight RT. Socioeconomic disparities affect prefrontal function in children. *Journal of Cognitive Neuroscience*. 2009; 21(6):1106–15. <http://doi.org/10.1162/jocn.2009.21101>. [PubMed: 18752394]
- Krishnadas R, McLean J, Batty GD, Burns H, Deans KA, Ford I, Cavanagh J. Socioeconomic deprivation and cortical morphology: psychological, social, and biological determinants of ill health study. *Psychosomatic Medicine*. 2013; 75(7):616–23. <http://doi.org/10.1097/PSY.0b013e3182a151a7>. [PubMed: 23975946]
- Kuhl PK, Conboy BT, Coffey-Corina S, Padden D, Rivera-Gaxiola M, Nelson T. Phonetic learning as a pathway to language: new data and native language magnet theory expanded (NLM-e). *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2008; 363(1493):979–1000. <http://doi.org/10.1098/rstb.2007.2154>.
- Lee Y-S, Turkeltaub P, Granger R, Raizada RDS. Categorical speech processing in Broca's area: an fMRI study using multivariate pattern-based analysis. *The Journal of Neuroscience*. 2012; 32(11):3942–8. <http://doi.org/10.1523/JNEUROSCI.3814-11.2012>. [PubMed: 22423114]
- Liu H, Kuhl P, Tsao F. An association between mothers' speech clarity and infants' speech discrimination skills. *Developmental Science*. 2003; 3:1–10. Retrieved from <http://onlinelibrary.wiley.com/doi/10.1111/1467-7687.00275/full>.
- Mayes LC, Bornstein MH. Infant information-processing performance and maternal education. *Early Development and Parenting*. 1995; 4:91–96.
- Monzalvo K, Fluss J, Billard C, Dehaene S, Dehaene-Lambertz G. Cortical networks for vision and language in dyslexic and normal children of variable socio-economic status. *NeuroImage*. 2012; 61(1):258–274. <http://doi.org/10.1016/j.neuroimage.2012.02.035>. [PubMed: 22387166]
- Moon C, Lagercrantz H, Kuhl PK. Language experienced in utero affects vowel perception after birth: a two-country study. *Acta Paediatrica*. 2013; 102(2):156–60. <http://doi.org/10.1111/apa.12098>. [PubMed: 23173548]
- Myers E, Blumstein S, Walsh E, Eliassen J. Inferior frontal regions underlie the perception of phonetic category invariance. *Psychological Science*. 2009; 20(7):895–903. <http://doi.org/10.1111/j.1467-9280.2009.02380.x.Inferior>. [PubMed: 19515116]
- Noble KG, Houston SM, Kan E, Sowell ER. Neural correlates of socioeconomic status in the developing human brain. *Developmental Science*. 2012; 15(4):516–27. <http://doi.org/10.1111/j.1467-7687.2012.01147.x>. [PubMed: 22709401]

- Noble KG, McCandliss BD, Farah MJ. Socioeconomic gradients predict individual differences in neurocognitive abilities. *Developmental Science*. 2007; 10(4):464–80. <http://doi.org/10.1111/j.1467-7687.2007.00600.x>. [PubMed: 17552936]
- Noble KG, Norman MF, Farah MJ. Neurocognitive correlates of socioeconomic status in kindergarten children. *Developmental Science*. 2005; 8(1):74–87. <http://doi.org/10.1111/j.1467-7687.2005.00394.x>. [PubMed: 15647068]
- Noordenbos MW, Serniclaes W. The categorical perception deficit in dyslexia: A meta-analysis. *Scientific Studies of Reading*. 2015; 19(5):1–20. <http://doi.org/10.1080/10888438.2015.1052455>.
- Otero G. Poverty, cultural disadvantage and brain development: a study of pre-school children in Mexico. *Electroencephalography and Clinical Neurophysiology*. 1997; 102(6):512–6. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/9216484>. [PubMed: 9216484]
- Otero G, Pliego-Rivero F, Fernandez T, Ricardo J. EEG development in children with sociocultural disadvantages: a follow-up study. *Clinical Neurophysiology*. 2003; 114(10):1918–1925. [http://doi.org/10.1016/S1388-2457\(03\)00173-1](http://doi.org/10.1016/S1388-2457(03)00173-1). [PubMed: 14499754]
- Perfetti B, Saggino A, Ferretti A, Caulo M, Romani GL, Onofri M. Differential patterns of cortical activation as a function of fluid reasoning complexity. *Human Brain Mapping*. 2009; 30(2):497–510. <http://doi.org/10.1002/hbm.20519>. [PubMed: 18095280]
- Prabhakaran V, Smith JA, Desmond JE, Glover GH, Gabrieli JD. Neural substrates of fluid reasoning: an fMRI study of neocortical activation during performance of the Raven's Progressive Matrices Test. *Cognitive Psychology*. 1997; 33(1):43–63. <http://doi.org/10.1006/cogp.1997.0659>. [PubMed: 9212721]
- Raizada RDS, Richards TL, Meltzoff A, Kuhl PK. Socioeconomic status predicts hemispheric specialization of the left inferior frontal gyrus in young children. *NeuroImage*. 2008; 40(3):1392–401. <http://doi.org/10.1016/j.neuroimage.2008.01.021>. [PubMed: 18308588]
- Raviv T, Kessenich M, Morrison FJ. A mediational model of the association between socioeconomic status and three-year-old language abilities: the role of parenting factors. *Early Childhood Research Quarterly*. 2004; 19(4):528–547. <http://doi.org/10.1016/j.ecresq.2004.10.007>.
- Reilly S, Wake M, Ukoumunne OC, Bavin E, Prior M, Cini E, Bretherton L. Predicting language outcomes at 4 years of age: findings from Early Language in Victoria Study. *Pediatrics*. 2010; 126(6):e1530–7. <http://doi.org/10.1542/peds.2010-0254>. [PubMed: 21059719]
- Richlan F. Developmental dyslexia: dysfunction of a left hemisphere reading network. *Frontiers in Human Neuroscience*. 2012 May; 6:120. <http://doi.org/10.3389/fnhum.2012.00120>. [PubMed: 22557962]
- Richlan F, Kronbichler M, Wimmer H. Functional abnormalities in the dyslexic brain: a quantitative meta-analysis of neuroimaging studies. *Human Brain Mapping*. 2009; 30(10):3299–308. <http://doi.org/10.1002/hbm.20752>. [PubMed: 19288465]
- Riecker A, Brendel B, Ziegler W, Erb M, Ackermann H. The influence of syllable onset complexity and syllable frequency on speech motor control. *Brain and Language*. 2008; 107(2):102–13. <http://doi.org/10.1016/j.bandl.2008.01.008>. [PubMed: 18294683]
- Roberts E, Bornstein M. Early cognitive development and parental education. *Infant and Child Development*. 1998 May; 62:49–62. Retrieved from [http://onlinelibrary.wiley.com/doi/10.1002/\(SICI\)1522-7219\(199903\)8:1%253C49::AID-ICD188%253E3.0.CO;2-1/abstract](http://onlinelibrary.wiley.com/doi/10.1002/(SICI)1522-7219(199903)8:1%253C49::AID-ICD188%253E3.0.CO;2-1/abstract).
- Rowe ML. Child-directed speech: relation to socioeconomic status, knowledge of child development and child vocabulary skill. *Journal of Child Language*. 2008; 35(1):185–205. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/18300434>. [PubMed: 18300434]
- Rowe ML. A longitudinal investigation of the role of quantity and quality of child-directed speech in vocabulary development. *Child Development*. 2012; 83(5):1762–74. <http://doi.org/10.1111/j.1467-8624.2012.01805.x>. [PubMed: 22716950]
- Sheridan MA, Sarsour K, Jutte D, D'Esposito M, Boyce WT. The impact of social disparity on prefrontal function in childhood. *PLOS ONE*. 2012; 7(4):e35744. <http://doi.org/10.1371/journal.pone.0035744>. [PubMed: 22563395]
- Skoe E, Krizman J, Kraus N. The impoverished brain: disparities in maternal education affect the neural response to sound. *Journal of Neuroscience*. 2013; 33(44):17221–31. <http://doi.org/10.1523/JNEUROSCI.2102-13.2013>. [PubMed: 24174656]

- Spreng RN, Sepulcre J, Turner GR, Stevens WD, Schacter DL. Intrinsic architecture underlying the relations among the default, dorsal attention, and frontoparietal control networks of the human brain. *Journal of Cognitive Neuroscience*. 2013; 25(1):74–86. http://doi.org/10.1162/jocn_a_00281. [PubMed: 22905821]
- Stevens C, Lauinger B, Neville H. Differences in the neural mechanisms of selective attention in children from different socioeconomic backgrounds: an event-related brain potential study. *Developmental Science*. 2009; 12(4):634–646. <http://doi.org/10.1111/j.1467-7687.2009.00807.x>. [PubMed: 19635089]
- Talairach, J., Tournoux, P. *Co-Planar Stereotaxic Atlas of the Human Brain: 3-Dimensional Proportional System: An Approach to Cerebral Imaging*. New York: Thieme; 1988. Retrieved from <http://books.google.com/books?hl=en&lr=&id=ssEbmvcJT8C&pgis=1>
- Tomarken AJ, Dichter GS, Garber J, Simien C. Resting frontal brain activity: linkages to maternal depression and socio-economic status among adolescents. *Biological Psychology*. 2004; 67(1–2): 77–102. <http://doi.org/10.1016/j.biopsycho.2004.03.011>. [PubMed: 15130526]
- Tsao F-M, Liu H-M, Kuhl PK. Speech perception in infancy predicts language development in the second year of life: a longitudinal study. *Child Development*. 2004; 75(4):1067–84. <http://doi.org/10.1111/j.1467-8624.2004.00726.x>. [PubMed: 15260865]
- Vaden KI, Kuchinsky SE, Cute SL, Ahlstrom JB, Dubno JR, Eckert MA. The cingulo-opercular network provides word-recognition benefit. *Journal of Neuroscience*. 2013; 33(48):18979–86. <http://doi.org/10.1523/JNEUROSCI.1417-13.2013>. [PubMed: 24285902]
- Wagner, RK., Torgesen, JK., Rashotte, CI. *The Comprehensive Test of Phonological Processing*. Austin: Pro-Ed; 1999.
- Wechsler, D. *Wechsler Abbreviated Scale of Intelligence*. San Antonio: The Psychological Corporation; 1999.
- Werker JF, Tees RC. Phonemic and phonetic factors in adult cross-language speech perception. *The Journal of the Acoustical Society of America*. 1984; 75(6):1866–78. Retrieved from <http://www.ncbi.nlm.nih.gov/pubmed/6747097>. [PubMed: 6747097]
- Wild CJ, Yusuf A, Wilson DE, Peelle JE, Davis MH, Johnsrude IS. Effortful listening: the processing of degraded speech depends critically on attention. *Journal of Neuroscience*. 2012; 32(40):14010–21. <http://doi.org/10.1523/JNEUROSCI.1528-12.2012>. [PubMed: 23035108]
- Wilkinson, GS. *Wide Range Achievement Test - Third Edition*. Wilmington, DE: Wide Range, Inc.; 1993.
- Ziegler JC, Pech-Georgel C, George F, Lorenzi C. Noise on, voicing off: Speech perception deficits in children with specific language impairment. *Journal of Experimental Child Psychology*. 2011; 110(3):362–372. <http://doi.org/10.1016/j.jecp.2011.05.001>. [PubMed: 21663919]

Highlights

- Maternal education (ME) was related to IQ, vocabulary, and phonological awareness.
- An ME-by-categorical-perception interaction was seen for nonverbal reasoning.
- An interaction was seen in left frontal cortex for phonemic perception.
- Results highlight importance of examining SES effects at different ability levels.

Figure 1.
Correlations between maternal education and Matrix Reasoning performance in the Low and High Categorical Perception Index groups.

Figure 2.

Partial regression plots showing the relationships between maternal education and (A) estimated IQ, (B) Vocabulary, and (C) Elision in the full sample after removing the linear effects of the Categorical Perception Index.

Figure 3. Regions showing a significant Categorical Perception Index (CPI)-by-maternal education interaction effect in the full sample in the phonemic condition, and partial regression plots showing the relationships between maternal education and the average beta values across the region of the interaction effect in the Low and High CPI groups after controlling for age.

Table 1

The effects of maternal education (ME) and the interaction of the Categorical Perception Index (CPI) and ME on the neuropsychological variables, with the associated standardized regression coefficient (β), squared semipartial correlation coefficient (sr^2), and corrected p value.

Dependent Variable	Regressor	β	sr^2	Corrected p
WASI Estimated FSIQ	ME	.450	.203	.028
WASI Vocabulary	ME	.463	.214	.028
WASI Matrix Reasoning	ME	.372	.135	.054
	CPI $\times$ ME	-.449	.186	.028
CTOPP Elision	ME	.355	.126	.069
CTOPP RLN	ME	.278	.077	.148
WRAT-3 Reading	ME	.185	.034	.317

Note. WASI = Wechsler Abbreviated Scale of Intelligence; FSIQ = Full Scale IQ; CTOPP = Comprehensive Test of Phonological Processing; RLN = Rapid Letter Naming; WRAT-3 = Wide Range Achievement Test-3.

Table 2

Regions showing a significant Categorical Perception Index-by-maternal education interaction for the full sample in the phonemic condition with cluster size (volume in mm³), z-scores (Max), Talairach coordinates (x, y, z), and location of local maxima in each cluster.

Cluster Size	Max	x	y	z	Location
12200	-4.2	-41	24	42	L middle frontal gyrus
	-3.4	-41	34	-2	L inferior frontal gyrus, pars orbitalis
	-3.0	-6	44	42	L superior frontal gyrus
	-3.0	-42	21	14	L inferior frontal gyrus, pars triangularis

Note. L = Left, R = Right