Home Math Environment Predicts Neural Differentiation for Symbolic Number Processing in Preschoolers

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Synopsis

The relation between the Home Math Environment and neural specialization was investigated in 48 preschoolers. Hemodynamic activity was acquired using fNIRS during symbolic and nonsymbolic number tasks. While behavioral accuracy was not associated with home activities, neural activation patterns were significantly predicted by the frequency of math activities. Specifically, greater hemodynamic differentiation between difficult and easy symbolic trials was observed in the left parietal cortex ($b=0.46$, $p<.001$). This effect remained significant after controlling for parental education. Results are interpreted within the Interactive Specialization framework, suggesting that environmental inputs drive neural tuning before behavioral effects emerge.

Background

Early numerical skills are strong predictors of later academic achievement (Duncan et al., 2007). While behavioral research links the Home Math Environment (HME) to these skills, the neurobiological mechanisms underlying this experience-dependent plasticity remain unclear. The Interactive Specialization framework posits that functional neural specialization emerges through environmental interaction (Johnson, 2011), particularly in the left parietal cortex, which becomes specialized for symbolic number processing over development. In this study, we investigated whether variations in the home environment relate to this neural specialization. We hypothesized that the frequency of parent-child math activities would predict the degree of functional specialization, specifically the hemodynamic differentiation between difficult and easy symbolic trials, in the left parietal cortex of 4 to 6 year olds.

Methods

48 children between four and six years of age (M=5.1 years; SD=6 months) and their primary caregivers participated in this study. The HME was assessed via a parental questionnaire regarding the frequency of number-related activities engaged in with the child.

Hemodynamic activity was acquired using NIRSport2 fNIRS system (NIRx Medical Technologies LLC). Optodes were positioned over the bilateral inferior frontal and inferior parietal regions, creating 16 channel montage.

The experimental protocol consisted of 8 blocks per task, with 6 trials per block. Difficulty levels (specific ratios or distances) were separated into distinct blocks. Both trial and block sequences were randomized, and task order was counterbalanced across participants. Stimuli appeared for

2s, followed by a 1.5s inter-stimulus interval. Blocks were separated by a pseudo-randomized 12-16s fixation period.

fNIRS data pre-processing was performed using. Raw optical signals were converted to optical density (OD) changes. Spline Savitzky-Golay filter was applied for motion correction. Then, OD was used to compute the concentration changes of oxygenated (HbO) and deoxygenated hemoglobin (HbR). HbO signals were bandpass filtered between 0.008-0.2Hz and truncated with a 3s pre-stimulus baseline and 12s post-stimulus period. A neurovascular coupling (NVC) parameter was calculated by first computing the mean HbO amplitude within the first 10s following stimulus onset. The mean HbO signal within this temporal window was then baseline corrected by subtracting the mean HbO amplitude of the pre-stimulus and normalized by dividing it by the standard deviation of the pre-stimulus. NVC parameters were first computed at the channel level. NVC parameters were averaged across the four channels of each ROI.

Statistical inference relied on linear mixed-effects models, specifically testing the three-way interaction between Task, Difficulty, and Home Math Activities on left parietal activation, while controlling for age and random effects.

Results

Behavioral analyses revealed expected main effects of difficulty and age on accuracy; however, adding HME variables to behavioral models did not improve model fit.

fNIRS results indicated that the frequency of math activities predicted neural activation patterns. The LMM for the left parietal ROI revealed a significant Task×Difficulty×Math Activities interaction. Decomposition indicated that for the SN Task, math activities predicted the activation difference between easy and difficult trials (b=0.46, p<.001). Specifically, children with richer home math activities showed greater differentiation of difficult versus easy items in the left parietal ROI. This effect was not observed for the NN Task (p=.296) and remained significant after controlling for parental education and reading activities, indicating the specificity of the relation.

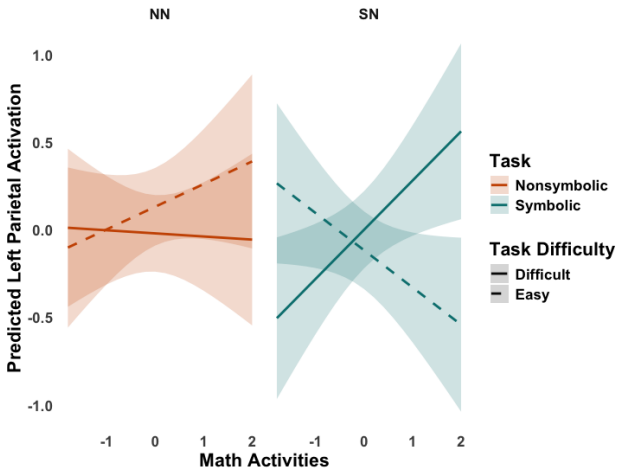

Figure 1. Left parietal activation vary as a function of task, difficulty and degree of math activities families engage in.

Discussion

Our findings demonstrate, for the first time in preschoolers, that the frequency of parent-child math activities predicts the degree of functional specialization in the left parietal cortex for symbolic number processing. The observation that children with richer home math experiences exhibited greater hemodynamic differentiation between difficult and easy symbolic trials aligns with the Interactive Specialization account. This framework posits that functional neural specialization emerges gradually through interaction with experience-dependent environmental.

Our results suggest that the left parietal cortex is particularly susceptible to such environmental influences during early development. Notably, this neural tuning was specific to math activities, persisting after controlling for socioeconomic status and reading activities, and specific to the symbolic domain, as no such relation was found for NN processing.

Interestingly, we observed brain-environment relations in the absence of behavior-environment relations. This suggests that neural measures may be more sensitive to variations in the home environment than behavioral measures at this developmental stage. Furthermore, the relation between home math activities and left parietal activation remained significant after controlling for parental education and home reading activities, indicating the specificity of this relation to math-related environmental input.

While the cross-sectional design limits causal inferences, these findings suggest that the HME plays a role in the functional specialization of the brain regions underlying SN processing. Future longitudinal interventions are needed to determine the causal direction of these effects.

References

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