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Nurturing the Mathematical Brain: Home Numeracy Practices Are Associated With Children's Neural Responses to Arabic Numerals

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Abstract

Disparities in home numeracy environments contribute to variations in children's mathematical skills. However, the neural mechanisms underlying the relation between home numeracy experiences and mathematical learning are unknown. Here, parents of 66 eight-year-olds completed a questionnaire assessing the frequency of home numeracy practices. Neural adaptation to the repetition of Arabic numerals and words was measured in children using functional MRI (n = 50) to assess how sensitive the brain is to the presentation of numerical and nonnumerical information. Disparities in home numeracy practices were related to differences in digit (but not word) processing in a region of the left intraparietal sulcus (IPS) that was also related to children's arithmetic fluency. Furthermore, digit-related processing in the IPS influenced the relation between home numeracy practices and arithmetic fluency. Results were consistent with a model hypothesizing that home numeracy practices may affect children's mathematical skills by modulating the IPS response to symbolic numerical information.

Keywords

home numeracy practices, numerical brain, open data, open materials

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Children's mathematical development is characterized by large individual differences that critically impact career prospects in a technology-driven society. Although these individual differences are often attributed to school-related factors (Sokolowski & Ansari, 2018), variations in mathematical achievement through elementary and middle school are predicted by disparities in numerical knowledge even before children enter kindergarten (Duncan et al., 2007). This suggests that experiences with numeracy outside of the classroom might influence the acquisition of numerical skills (Elliott & Bachman, 2018).

Current neuroimaging research suggests that children's home environment and experiences mainly affect mathematical learning by influencing language-related brain functions. For example, several studies have investigated the relation between brain development and family socioeconomic status (SES), a construct that includes measures of parental education and income and therefore serves as a proxy for children's environmental inputs and experiences (Farah, 2017). This literature has predominantly associated SES with structural differences in left perisylvian and prefrontal areas supporting language and executive functions (Farah, 2017). SES has also been associated with tasks that involve the left perisylvian language system in children (Merz et al.,

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2019). Finally, studies suggest that even the link between SES and mathematical knowledge is supported by language-related brain systems (Demir-Lira et al., 2015, 2016).

But prior studies have two major limitations. First, SES is a distal construct that may affect mathematical development through more proximal environmental factors. For instance, SES may be associated with the quality and frequency of mathematical activities and resources that are provided by parents at home—that is, the *home numeracy environment* (Dunst et al., 2017; Elliott & Bachman, 2018; Mutaf-Yıldız et al., 2020). Indeed, children who benefit from more frequent home numeracy practices than their peers show improved mathematical knowledge, though this relation depends on the type (formal vs. informal) and complexity (advanced vs. basic) of home practices (Elliott & Bachman, 2018). Thus, home numeracy practices may provide a more proximal index of a child's home numeracy environment than family SES.

Second, previous studies investigating the relation between SES and mathematical processing have exclusively focused on single-digit arithmetic (Demir-Lira et al., 2015, 2016). However, single-digit arithmetic largely relies on the retrieval of phonological information from long-term memory (Zamarian et al., 2009). This raises the possibility that the relation between SES and language-related areas observed in these studies may be due to the phonological nature of the task.

Cognitive neuroscience research suggests that human mathematical competence is likely not grounded in the brain systems for language (Amalric & Dehaene, 2016). Instead, studies show that nonsymbolic numerical processing (e.g., estimating the numerosity of an array of dots) as well as symbolic numerical processing (e.g., understanding the meaning of an Arabic numeral) involve brain circuits in and around the intraparietal sulcus (IPS; Nieder, 2016). Although a growing number of studies suggest that nonsymbolic and symbolic numerical processing do not rely on similar mechanisms in the IPS (Wilkey & Ansari, 2020), the progressive recruitment of that region is largely believed to support mathematical learning in children (Dehaene & Cohen, 2007). Individual differences in mathematical skills have also been shown to be associated with symbolic number processing in the IPS (Bugden et al., 2012), a finding in line with accumulating evidence suggesting that symbolic number understanding strongly predicts mathematical skills in children (to a greater extent than nonsymbolic estimation skills; De Smedt et al., 2013). Therefore, it is possible that children who experience more frequent numeracy activities at home may show enhanced response to symbolic numerical information in the IPS, which in turn may influence mathematical skills. This hypothesized model (Fig. 1a) parallels models positing that a supportive home literacy environment may influence the structure and function of language-related brain regions, which are then thought to affect children's linguistic skills (see Romeo et al., 2018, and Fig. 1 in Merz et al., 2020, for an example of such a model).

In the present study, we explored the relation between home numeracy practices and the brain circuits underlying symbolic numerical processing in children. We recruited 73 eight-year-olds with their parents. Although both parents and children completed the same test of arithmetic fluency (thereby measuring a skill that is at the heart of elementary mathematics and relates to higher-level mathematical competence; Price et al., 2013), parents also responded to a questionnaire assessing home numeracy practices (final behavioral sample: $N = 66$). Finally, children underwent functional MRI (fMRI) scanning (final fMRI sample: $n = 50$). In the scanner, children were presented with a blocked passive visual adaptation task inspired by the work of Perrachione and colleagues (2016). Functional MRI adaptation paradigms rely on the idea that presenting a given stimulus repeatedly leads to a decrease of signal in the region that processes this stimulus (because firing rates of the neuronal population decrease; Grill-Spector & Malach, 2001). Thus, comparing activity associated with blocks of different stimuli (no-adaptation block) with activity associated with blocks of

Statement of Relevance

Both before and after they enter school, children are exposed to vastly different numeracy experiences at home. Although these disparities are increasingly thought to affect mathematical achievement, little is known about how children's environments and experiences beyond the classroom impact the development of the numerical brain. Using functional MRI in 8-year-olds, we found that brain responses to the repeated presentation of symbolic numerical magnitudes (Arabic numerals) in the intraparietal sulcus (IPS) are related to differences in the frequency of numeracy practices shared with parents. Our findings are consistent with the proposal that the processing of symbolic magnitudes in the IPS mediates the relation between home numeracy practices and children's mathematical skills. Thus, children's home environments not only may affect language-related brain functions, as suggested by prior research, but also may influence the way symbolic numerical magnitudes are processed in the brain.

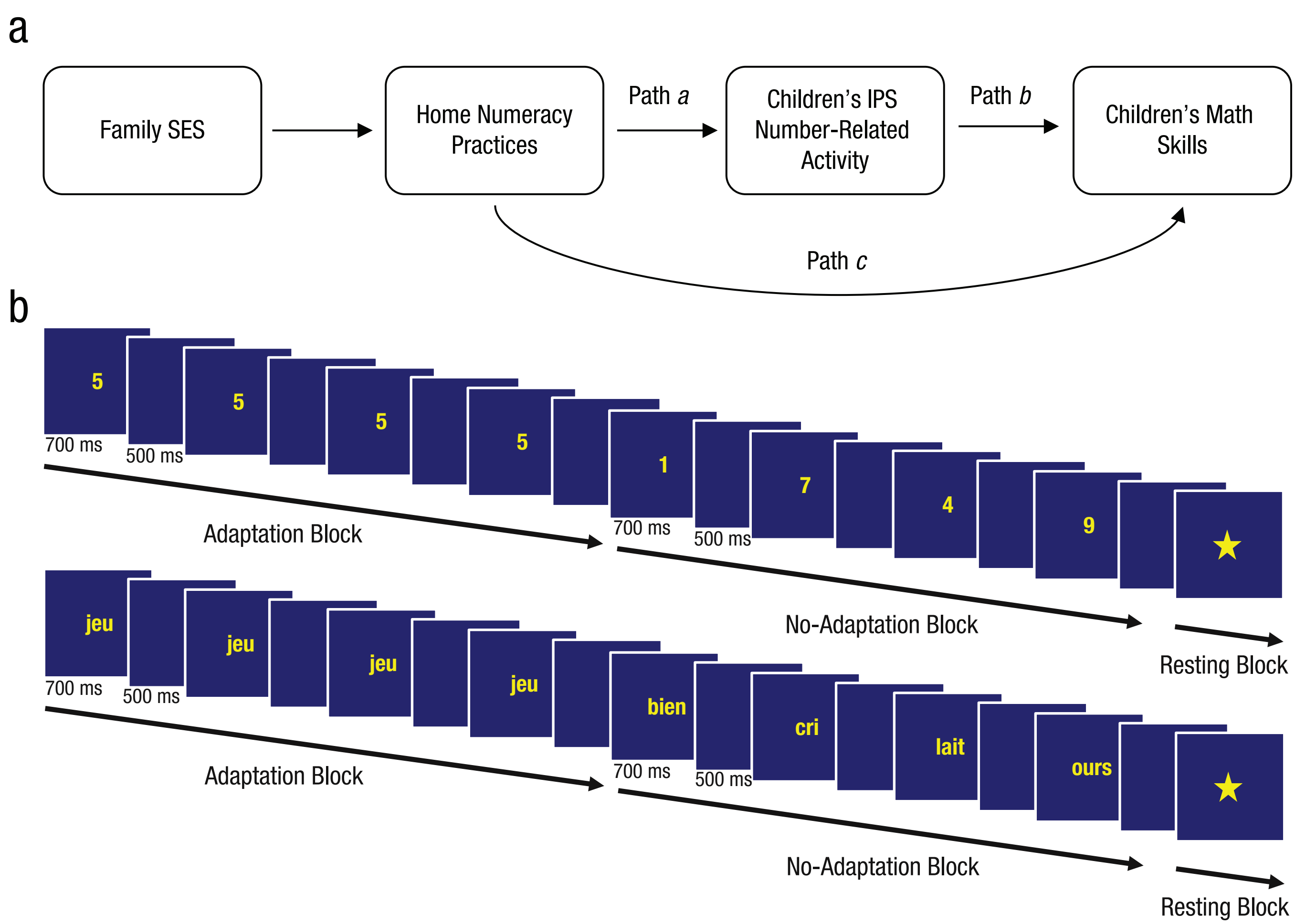

Fig. 1. Model and experimental design. The hypothesized model (a) shows the relations between family socioeconomic status (SES), home numeracy practices, children's intraparietal sulcus (IPS) number-related brain activity, and children's mathematical skills (adapted from a model of the relations between SES, home literacy practices, brain activity, and reading skills; Merz et al., 2020). Path *a* reflects whether home numeracy practices relate to neural adaptation. Path *b* reflects whether neural adaptation predicts arithmetic fluency (when home numeracy practices are controlled for). Path *ab* is the formal test of mediation, reflecting whether these effects are jointly strong enough to mediate the relation between home numeracy practices and arithmetic fluency, or path *c*. In the experimental task (b), participants were sequentially presented with digits (top) or words (bottom) that were either identical (adaptation blocks) or different (no-adaptation blocks). In adaptation blocks, the same stimulus was repeated eight times. In no-adaptation blocks, eight different stimuli were presented.

identical stimuli (adaptation block) captures a *neural-adaptation effect* in task-relevant regions. Here, children were presented with adaptation and no-adaptation blocks of either digits or words (the latter being considered a control; Fig. 1b).

Testing the causal aspects of the assumptions in Figure 1a required interventional designs, which are particularly challenging in pediatric neuroimaging. However, our cross-sectional design may still provide critical evidence for the plausibility of this model. Specifically, we aimed to test whether associations between home numeracy practices, digit processing in the IPS, and mathematical skills observed at age 8 are consistent with this model. This would mirror recent studies showing that relations between home literacy, language-related structure and function, and literacy skills are consistent with a model of how home literacy experiences affect literacy skills (Merz et al., 2020; Romeo et al., 2018).

Here we first aimed to confirm that home numeracy practices relate to children's arithmetic fluency (path *c* in Fig. 1a). We then used the framework of mass-univariate *mediation-effect parametric mapping* (MEPM; Wager et al., 2008) to assess (a) whether home numeracy practices relate to digit-related (but not word-related) activity in the IPS (path *a* in Fig. 1a); (b) whether digit-related (but not word-related) activity in the IPS relates to children's arithmetic fluency, after analyses control for home numeracy practices (path *b* in Fig. 1a); and (c) whether digit-related (but not word-related) IPS activity may explain some of the relation

Table 1. Demographic Information and Test Scores of Children and Parents in the Sample

	Behavioral sample (N = 66)		Functional MRI sample (n = 50)	
Variable	Children	Parents	Children	Parents
Age (years)[a]	8.46 (0.36)	39.53 (4.95)	8.48 (0.35)	39.74 (4.80)
Sex (female)	30%	89%	30%	86%
Child grade (second grade)[b]	30%		26%	
Parental education[c]		3.05 (2.36)		3.10 (2.57)
Approximate monthly income (euros)[d]		1,727 (1,078)		1,680 (1,101)
Arithmetic fluency (raw score)	40 (12)	122 (22)	41 (12)	122 (23)
Arithmetic fluency (standard score)	104 (24)	102 (9)	107 (24)	102 (10)
IQ composite (standard score)	112 (11)	—	112 (12)	—

Note: All values except sex and child grade are means (standard deviations are given in parentheses).
[a]All children were 8 years of age, except for one who was younger (7.51) and three who were slightly older (9.06 to 9.22) at the time of testing. [b]Children were in either second or third grade. [c]See the main text for an explanation about how parental education was calculated. [d]As a reference, the median monthly income in France is about €1,700 (Robin, 2019).

between home numeracy practices and children's arithmetic fluency. This would be consistent with the idea that home numeracy practices may affect children's numerical skills through symbolic numerical processing in the IPS.

Method

Participants

Seventy-three right-handed elementary school children of approximately 8 years of age and one of their parents were invited to participate in the experiment. Participants were contacted through flyers sent to schools and advertisements on social media. All parents and children came to the lab for a first behavioral session during which they were given tests and questionnaires. Seven children were excluded from the behavioral analyses because they (a) were seeing a speech-language pathologist on a regular basis (n = 3), (b) had an IQ lower than the 2.5th percentile (n = 2), (c) had a delay in speech and language acquisition (n = 1), or (d) were diagnosed with attention-deficit/hyperactivity disorder (n = 1). Therefore, 66 participants were included in the behavioral analyses of this first session (see also Girard et al., 2021, for additional behavioral analyses of that session). Fifty-eight of these children participated in a second session involving fMRI scanning with the digit- and word-adaptation tasks. After fMRI motion correction (see below), 50 children had at least one run of usable data in the digit-adaptation task (22 of these participants had two usable runs in that task), and 44 children had at least one run of usable data in the word-adaptation task (22 of these participants had two usable runs in that task). Details about justification of final fMRI sample sizes are given in the Supplemental Material available online, as well as sensitivity curves across a range of effect sizes for our samples (Fig. S1). Demographic information about children and parents can be found in Table 1. All children and parents were native French speakers. Parents gave written informed consent, and children agreed to participate in the study. The study was approved by a French ethics committee (Comité de Protection des Personnes Sud-Est 2). Families were paid €80 for their participation.

Testing

Arithmetic fluency of children and parents was assessed during the first session using the Math Fluency subtest of the Woodcock-Johnson III Tests of Achievement (Woodcock et al., 2001). In this test, participants solve simple addition, subtraction, and multiplication problems within a 3-min time limit. The test consists of two pages of 80 problems involving operands from 0 to 10. A raw score corresponding to the number of correct responses was obtained for each child and parent. An age-normalized score was also calculated on the basis of U.S. and French norms for adults and children, respectively (Schwartz et al., 2018). Given the homogeneity of the sample in terms of age (Table 1), raw scores were used in all analyses. In addition to mathematical skills, children's IQ was estimated using the Nouvelle Echelle Métrique de l'Intelligence-2 standardized intelligence test (Cognet, 2006). The test uses measures of verbal intelligence and matrix reasoning to provide a standardized score of full-scale IQ. Math Fluency and IQ scores are indicated in Table 1.

Parental questionnaires

Parents were given electronic questionnaires on a tablet to gather measures of home numeracy practices. First,

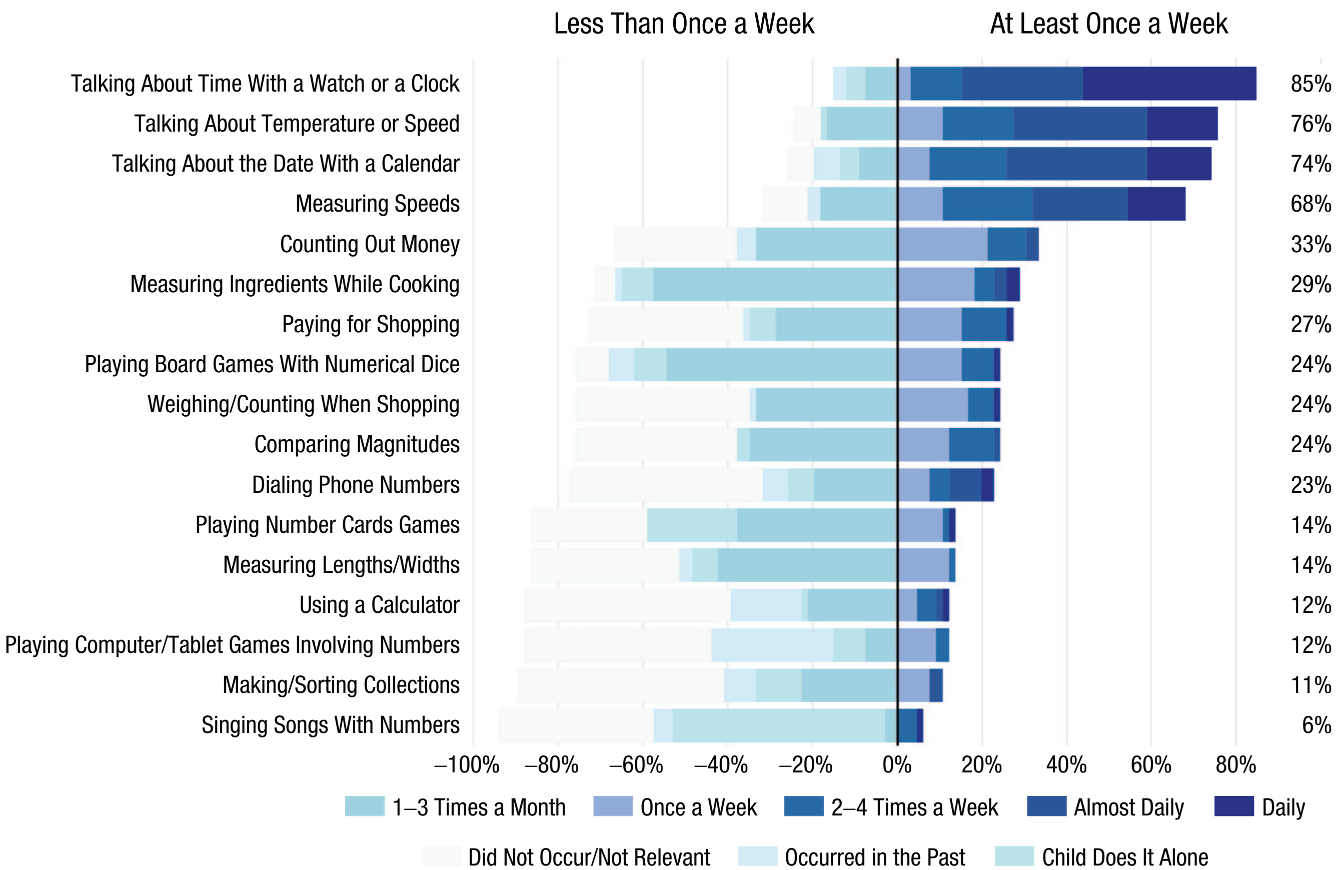

Fig. 2. Divergent stacked bar chart showing the frequencies of informal practices among parents ($N = 66$). Percentages on the right indicate the share of parents who engaged in each practice at least once a week. Practices are ordered from the most frequent (top) to the least frequent (bottom).

information about family SES was collected using parents' education level and monthly income. Education level was measured using the number of years completed before or after high school graduation, with high school graduation set at 0 (i.e., positive numbers indicated that parents completed some years of education after graduating). Approximate monthly income was measured using ranges with increments of €1,000. The minimum possible range was €0 to €999, and the maximum possible range was more than €10,000. For all analyses, we used the median of the reported income range (e.g., €500 for a range between €0 and €1,000) as an approximation of parents' income.

Second, parents were asked how often they engaged in home learning activities with their child that involved mathematics. To reduce the math focus of the study, we also asked parents about activities involving other academic and nonacademic domains (e.g., reading, music, biology). These items were considered filler items and were not analyzed in the present study. Activities were adapted from the questionnaire used by LeFevre et al. (2009). For each activity, parents rated the frequency with which they had engaged in that activity with their child at home during the past month. A 6-point rating scale was used (*did not occur/activity is not relevant to my child*, *1-3 times per month*, *once per week*, *2-4 times per week*, *almost daily*, and *daily*). Parents could also indicate whether they engaged in an activity in the past but no longer did at the time of testing ("The activity occurred in the past but no longer occurs"; rated 1 point). Finally, they could indicate whether the child engaged in that activity on his or her own ("My child does this activity without my help"; rated 1 point).

Among the 77 home learning activities mentioned in the questionnaire, 36 were related to mathematics. Following previous studies (LeFevre et al., 2009), we considered 17 of these activities to be informal (Fig. 2) and 19 to be formal (Fig. 3). Informal activities are those whose purpose is not to teach numerical skills but that nonetheless expose children to various mathematical concepts (e.g., using fractions when cooking; Elliott & Bachman, 2018; LeFevre et al., 2009; Mutaf-Yıldız et al., 2020). Formal activities are those in which parents

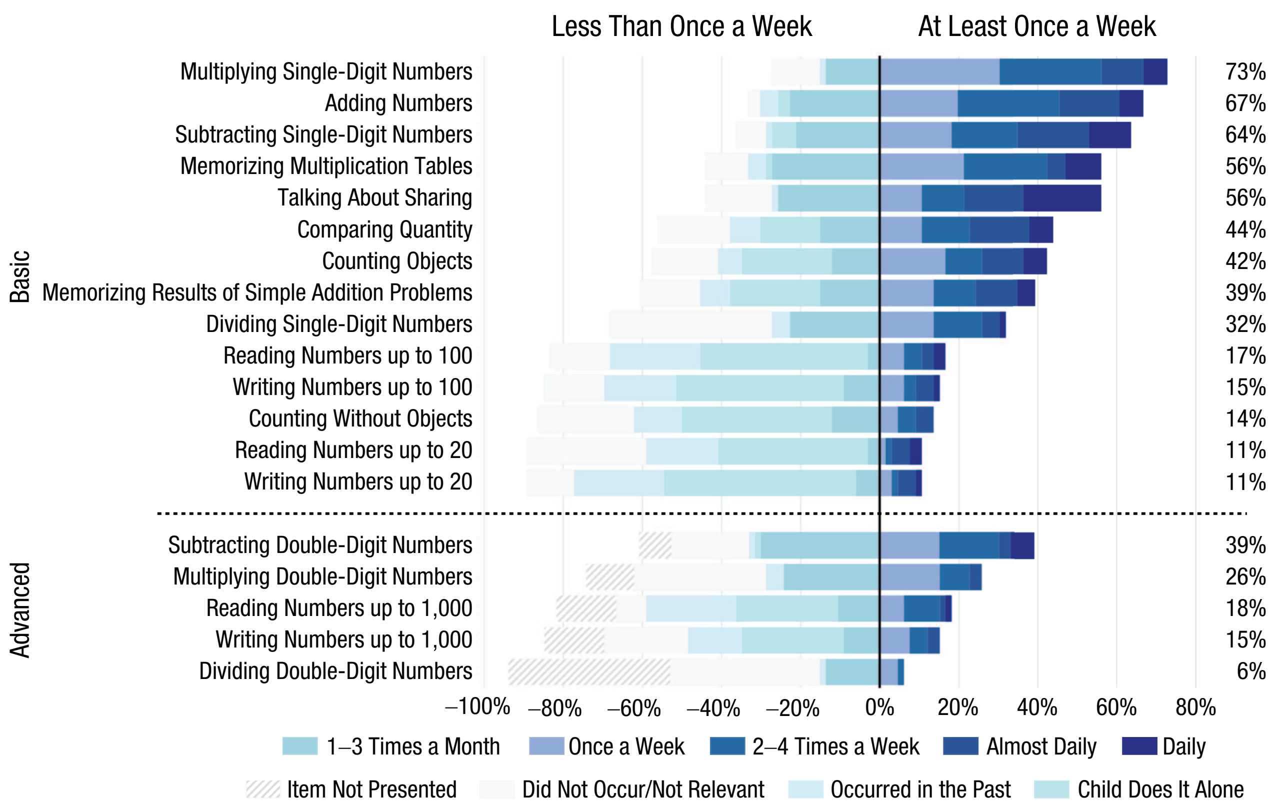

Fig. 3. Divergent stacked bar chart showing the frequencies of basic and advanced formal practices among parents (N = 66). Percentages on the right indicate the share of parents who engaged in each practice at least once a week. Practices are ordered from the most frequent (top) to the least frequent (bottom), separately for each level of complexity.

explicitly intend to teach numerical skills to their child (e.g., studying multiplication tables). Formal activities were further considered basic or advanced depending on their complexity for an 8-year-old child (Elliott & Bachman, 2018; Mutaf-Yıldız et al., 2020). For example, subtracting, multiplying, or dividing numbers was considered either basic or advanced depending on the size of the operands (i.e., single-digit vs. double-digit). Similarly, whereas activities such as reading and writing numbers up to 100 were considered relatively basic, reading and writing numbers up to 1,000 were considered more advanced in 8-year-olds. Thus, each advanced activity was always related to a more basic activity. To avoid having parents repeatedly answer "no" to questions that were about the same topic but differed only in terms of the complexity of the activity (e.g., "Did you count up to 100 with your child?" followed by "Did you count up to 1,000 with your child?"), we did not present advanced formal activities to parents if they stated that the corresponding more basic activity had never occurred at home. To account for the inherent relation between basic and advanced formal practices, we systematically included the frequency of basic practices as a covariate in models investigating the effects of advanced practices in both behavioral and fMRI analyses (and vice versa). Parental responses to the questionnaire are shown in Figures 2 and 3. Finally, parents were asked to provide a subjective estimate of their child's skills in mathematics (and other domains) using a 6-point rating scale (*not sure*, *severe difficulty*, *difficulty*, *average skills*, *good skills*, and *very good skills*).

Experimental tasks

We directly adapted a task from Perrachione et al. (2016) in which a series of symbolic stimuli were passively presented in blocks at the center of the screen. We chose this task because (a) it does not require an active response (it thereby avoids confounding individual differences in activity with individual differences in performance; Luna et al., 2010) and because (b) block designs have more power and reliability than event-related designs (which makes them particularly well suited for pediatric neuroimaging; Bennett & Miller, 2013). As in the study by Perrachione et al., one version of the task (i.e., the word-adaptation task) involved series of words. Words were three- to five-letter monosyllabic French nouns of equal frequency (mode = 4) obtained from the

OpenLexicon database (http://www.lexique.org/shiny/openlexicon/; Pallier & New, 2019). None of these words were number words or quantifiers. This word-adaptation task served as a control task in the present study. In another version of the task specifically developed for the purpose of the current study (i.e., the digit-adaptation task), words were replaced by Arabic numerals ranging from 1 to 8. Word- and digit-adaptation tasks were each composed of two runs. In each of these runs, participants were presented with adaptation and no-adaptation blocks (Fig. 1b). Adaptation blocks consisted of the repetition of the same stimulus (word or digit) eight times. No-adaptation blocks consisted of the presentation of eight different stimuli.

Experimental timeline

The experimental timeline was identical to that used by Perrachione et al. (2016). The task was presented using *PsychoPy2* (Version 1.81; Peirce et al., 2019). In each block of the adaptation tasks, stimuli (word or digit) remained on the screen for 700 ms, and there was a 500-ms interstimulus interval between each one (total block duration = 9.6 s). Ten adaptation blocks and 10 no-adaptation blocks were presented along with 10 blocks of visual fixation (duration = 9.6 s) in each run. Block presentation was pseudorandomized such that two blocks of the same type could not follow each other.

To ensure that tasks did not differ in levels of attentional engagement, we programmed a target stimulus (a picture of a rocket) to randomly appear 10 times in each run outside of the blocks. Participants were asked to press a button every time this target appeared. On average, children detected 90% of targets (SD = 18) in the digit-adaptation task and 89% of targets (SD = 15) in the word-adaptation task. There was no difference in target-detection rate between tasks (Wilcoxon rank-sum test: p = .73), indicating that children paid equal attention to the stimuli in both tasks. Spearman rank correlations indicated that target-detection rates were not correlated with education, income, home numeracy practices, or children's arithmetic fluency in any of the tasks (digit adaptation: all ρs < .16, all ps > .14; word adaptation: all ρs < .19, all ps > .11).

fMRI data preprocessing

Details about fMRI data acquisition are given in the Supplemental Material. Functional images were corrected for slice-acquisition delays and spatially realigned to the first image of the first run to correct for head movements. Realigned images were smoothed with a Gaussian filter (4 × 4 × 7 mm, full width at half maximum). Following Romeo et al. (2018), we used *ArtRepair* (Version 5b; https://cibsr.stanford.edu/tools/human-brain-project/artrepair-software.html; Mazaika et al., 2009) to identify functional volumes with a global mean intensity greater than 3 standard deviations from the average of the run or a volume-to-volume motion greater than 2 mm. These outlier volumes were substituted by the interpolation of the two nearest nonrepaired volumes. Participants with outliers in more than 20% of volumes were excluded from the analyses. After outlier exclusion, the movement range was on average 0.02 mm (SD = 0.07), 0.14 mm (SD = 0.30), and 0.18 mm (SD = 0.60) in the x, y, and z direction, with 0.24 (SD = 0.82), 0.32 (SD = 1.10), and 0.40 (SD = 0.37) degrees of roll, pitch, and yaw, respectively. Finally, functional images were normalized into the standard Montreal Neurological Institute (MNI) space (normalized voxel size, 2 × 2 × 3.5 mm^3).

fMRI data analysis

General linear models were used to analyze fMRI data. The scripts used to analyze fMRI data were created and run in MATLAB (The MathWorks, Natick, MA) and are available via GitHub at https://github.com/BBL-lab/BBL-batch-system. Brain activity associated with periods of adaptation and no-adaptation was modeled as epochs with onsets time locked to the beginning of each block and a duration of 9.6 s. All 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.

For each participant and task, the neural-adaptation effect was measured across the whole brain by subtracting activity associated with adaptation blocks from activity associated with no-adaptation blocks. Relations between home numeracy practices, neural-adaptation effects, and arithmetic fluency were assessed using the mass-univariate MEPM framework implemented in the multilevel mediation and moderation (M3) toolbox (available via GitHub at https://github.com/canlab/MediationToolbox; Wager et al., 2008). MEPM is a form of structural equation modeling that allows for the voxelwise mapping of multiple brain regions that satisfy the formal criteria for mediators in a standard three-variable path model involving a predictor, a brain response, and an outcome. For each voxel, MEPM estimates three paths: (a) path a (i.e., the relation between the predictor and the brain response), (b) path b (i.e., the relation between the brain response and the outcome when the predictor is controlled for), and (c) path ab (i.e., the formal test of mediation, indicating whether the relation between the predictor and the outcome, or path c, is significantly reduced when the brain response is included in the model). Here, path a reflects whether home numeracy practices relate to neural adaptation.

Path *b* reflects whether neural adaptation predicts arithmetic fluency (when home numeracy practices are controlled for). Path *ab* is the formal test of mediation, reflecting whether these effects are jointly strong enough to mediate the relation between home numeracy practices and arithmetic fluency (see Fig. 1a).

Bias-corrected bootstrap tests with 1,000 iterations were performed to estimate statistical significance at each voxel. Bootstrapping was used as a formal test of mediation because this method is more powerful to assess mediation than the Sobel test for small to moderate sample sizes (Shrout & Bolger, 2002). One-sided voxelwise maps of p values for paths *a*, *b*, and *ab* were corrected for multiple comparisons using Analysis of Functional NeuroImages (AFNI) 3dClustSim (Version AFNI_20.3.01; Cox et al., 2017; version update accounts for software bugs identified by Eklund et al., 2016). Smoothness estimates entered into 3dClustSim were spatial autocorrelation function (ACF) parameters averaged from each individual's first-level model residuals as calculated by 3dFWHMx using a whole-brain mask (ACF parameters: $x = 0.452647$, $y = 4.07555$, $z = 16.563$). Given the a priori focus in the study on the IPS, clusters were considered significant at a family-wise error (FWE) corrected threshold of $p < .05$, either across the whole brain or within an anatomical mask of the IPS (i.e., small-volume correction) defined using the Anatomy Toolbox (Version 2.2; Eickhoff et al., 2005). The IPS mask consisted of voxels with at least 50% probability of belonging to one of the IPS subdivisions (hIP1, hIP2, and hIP3), as defined in the Anatomy Toolbox. The same mask was used for similar small-volume corrections in our previous studies (e.g., Schwartz et al., 2018). FWE-corrected clusters (defined using facewise bordering, or nearest neighbor = 1) are reported using an uncorrected voxelwise threshold of $p = .0025$. Note that because path *a* and path *b* effects are conditionally independent, the probability of voxels from each path being significant by chance is therefore $p = .00000625$ or lower. Because our hypotheses were directional (i.e., we were interested only in lesser activity in adaptation than no-adaptation blocks, as well as increases in either arithmetic fluency or neural-adaptation effects as a function of home numeracy practices), p values for behavioral and fMRI results are one-sided. Accordingly, only 95% lower-bound confidence intervals (CIs) are reported.

Results

Behavioral results

We first investigated the relations between SES, home numeracy practices, and arithmetic fluency across the entire behavioral sample ($N = 66$). As can be seen in Figures 2 and 3, there was large individual variability in the reported frequencies of home numeracy practices. Between parents, average responses on the rating scale ranged from 0.65 to 2.88 for informal practices ($M = 1.47$, $SD = 0.50$), from 0.143 to 4.64 for basic formal practices ($M = 1.68$, $SD = 0.85$), and from 0 to 3.80 for advanced formal practices ($M = 0.95$, $SD = 0.76$). After adjusting for differences in parental income, we found that relatively higher education was not associated with more frequent informal practices, partial $r(64) = -.14$, $p = .865$, 95% CI lower = −.33. There was also no positive relation between education and basic formal practices (after adjustment for parental income and advanced formal practices), partial $r(64) = -.32$, $p = .996$, 95% CI lower = −.49. However, relatively higher education was associated with more frequent advanced formal practices (after adjustment for parental income and basic formal practices), partial $r(64) = .23$, $p = .034$, 95% CI lower = .02 (Fig. 4a). Finally, there was no positive relation between parental income and any numeracy practices after adjustment for parental education (all rs < .13, all ps > .163). Therefore, more educated (but not necessarily wealthier) parents engaged in more frequent advanced formal numeracy practices with their children. Parental education was thus included as a covariate in all further analyses of home numeracy practices.

Children's arithmetic fluency was positively correlated with advanced formal practices (after adjustment for parental education and basic formal practices), partial $r(64) = .29$, $p = .008$, 95% CI lower = .09 (Fig. 4b). However, there was no positive correlation between children's arithmetic fluency and basic formal practices (after adjustment for parental education and advanced formal practices), partial $r(64) = -.09$, $p = .775$, 95% CI lower = −.29, or between children's arithmetic fluency and informal practices (after adjustment for parental education), partial $r(64) = .08$, $p = .274$, 95% CI lower = −.13. Thus, higher children's arithmetic fluency was associated with more frequent home numeracy practices but only when these practices were formal and relatively advanced. The MEPM analyses below thus focus on these advanced formal practices.

MEPM results: digit adaptation

We used the framework of MEPM to evaluate the relations between advanced formal numeracy practices, neural adaptation to digits, and children's arithmetic fluency (controlling for education and basic formal numeracy practices). The results of these analyses are shown in Figure 5. First, consistent with the hypothesis that home numeracy practices influence the neural processing of digits (path *a*), results showed a significant positive relation between the frequency of advanced formal home numeracy practices and digit adaptation in a cluster of the left IPS ($x = -34$, $y = -60$, $z = 55$),

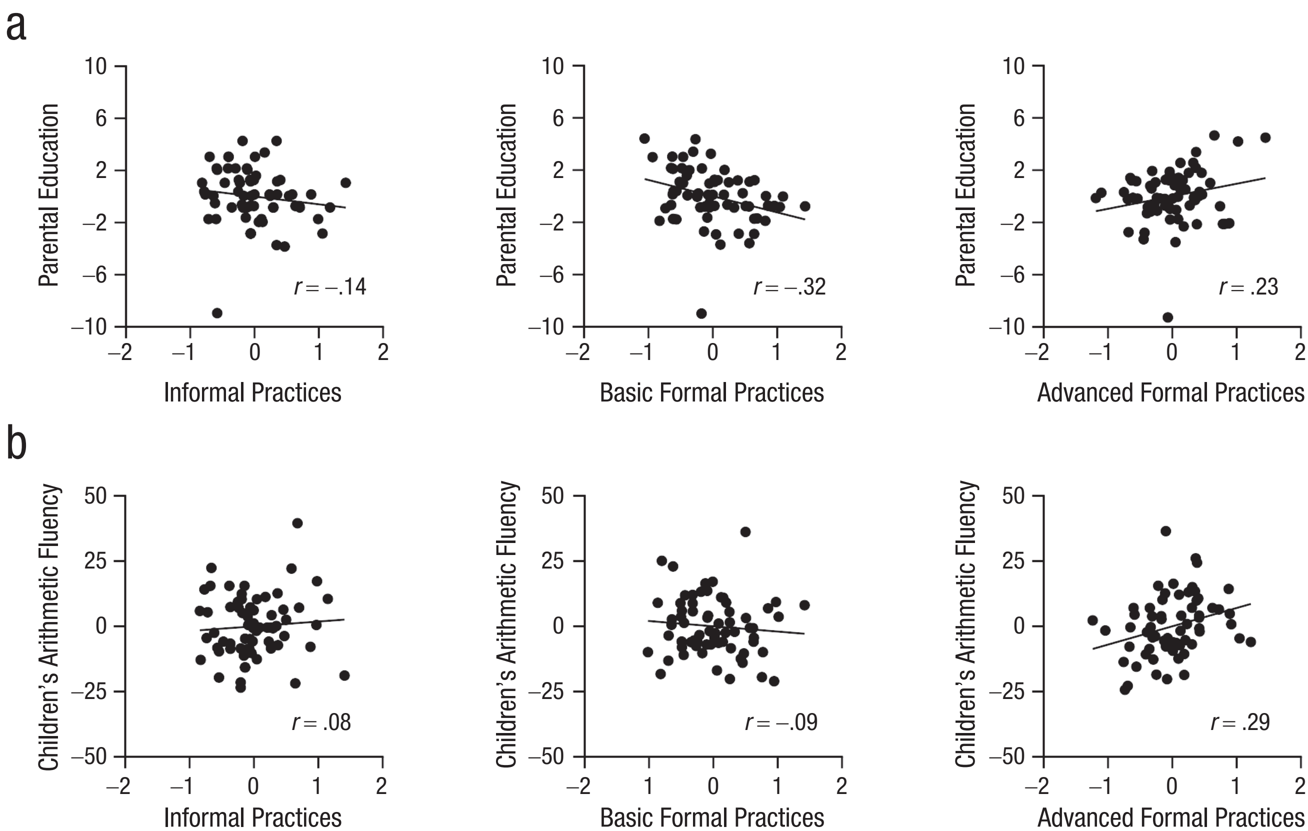

Fig. 4. Relations between socioeconomic status (SES), home numeracy practices, and children's mathematical skills (N = 66). Parental education (a) and children's arithmetic fluency (b) are each shown separately as a function of informal numeracy practices (left), basic formal numeracy practices (adjusted for advanced formal numeracy practices; center), and advanced formal numeracy practices (adjusted for basic formal numeracy practices; right). Correlations in (a) are also adjusted for parental income, and correlations in (b) are also adjusted for parental education. All variables are mean centered. Solid lines indicated best-fitting regressions.

cluster size = 0.1 cc, –log10 (maximum p value) = 2.75, r(48) = .35 (Fig. 5a, left). This indicates greater neural adaptation to digits in children who were exposed to more frequent numeracy practices. Second, controlling for advanced formal practices, we found a significant positive relation between digit adaptation and children's arithmetic fluency in several frontal, parietal, and occipital regions, including the right middle occipital gyrus (x = 32, y = −84, z = 6), cluster size = 9.2 cc, –log10 (maximum p value) = 6.84, r(48) = .59; the left superior frontal gyrus (x = −18, y = 50, z = 17), cluster size = 4.9 cc, –log10 (maximum p value) = 6.53, r(48) = .54; the right middle frontal gyrus (x = 42, y = 26, z = 17), cluster size = 1.9 cc, –log10 (maximum p value) = 3.77, r(48) = .45; and the left IPS (x = −34, y = −60, z = 55), cluster size = 0.3 cc, –log10 (maximum p value) = 4.51, r(48) = .44. This showed that children who exhibited greater neural adaptation in these regions also showed higher levels of arithmetic fluency (Fig. 5a, right). Finally, the formal test of mediation identified one cluster in the left IPS (x = −34, y = −60, z = 55), cluster size = 0.1 cc, –log10 (maximum p value) = 3.05, in which digit adaptation explained the relation between advanced numeracy practices and children's arithmetic fluency (Fig. 5b). This suggests that the neural processing of symbolic numerical information in the IPS mediates the relation between home numeracy practices and children's mathematical skills (path ab). The partially standardized effect size of this indirect effect (i.e., ratio of the indirect effect to the standard deviation of the outcome; Hayes, 2018) in the left IPS cluster was 0.35. Therefore, arithmetic fluency increased by 0.35 standard deviations for every 1-unit increase in frequency of reported advanced formal practices indirectly via digit adaptation in the IPS. The relation between advanced formal practices and children's arithmetic fluency in the fMRI sample—total effect, or path c: partial r(48) = .30, p = .017, 95% CI lower = .07 (Fig. 5c, left)—was no longer significant after we accounted for digit adaptation in the left IPS cluster identified in the formal test of mediation—direct effect, or path c': partial r(48) = .15, p = .146, 95% CI lower = −.09 (Fig. 5c, right).

It is important, however, to acknowledge that our design was cross-sectional. Therefore, advanced formal

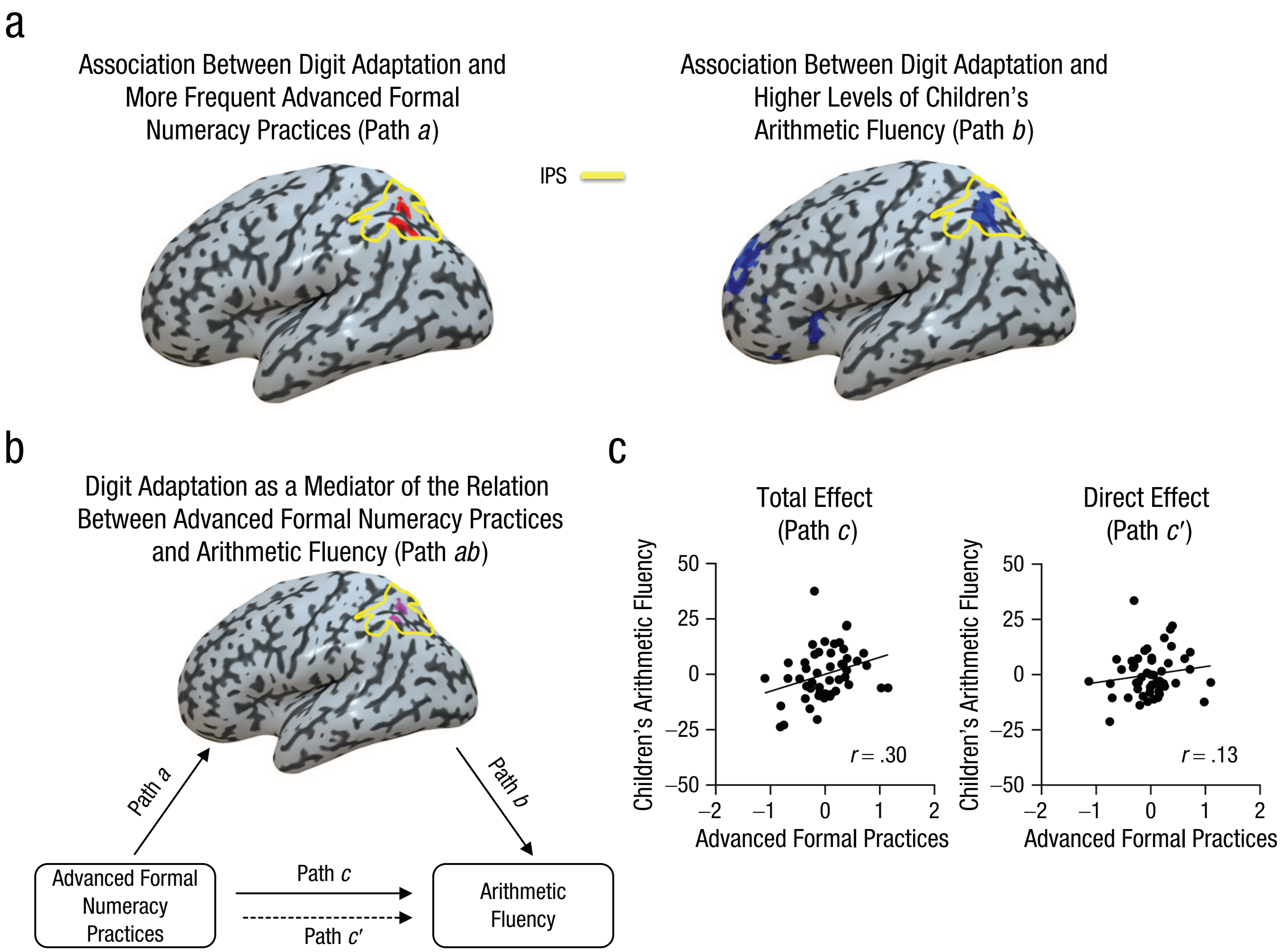

Fig. 5. Mediation-effect parametric-mapping analysis of the digit-adaptation task (n = 50). The brain images in (a) show activations in the left hemisphere in response to the influence of digit adaptation on advanced formal numeracy practices (path *a*, left) and children's arithmetic fluency (adjusted for advanced formal numeracy practices; path *b*, right). The mediation diagram (b) shows voxels in which digit adaptation influenced the relation between advanced formal numeracy practices and children's arithmetic fluency (path *ab*). The scatterplots (c) show children's arithmetic fluency as a function of advanced formal numeracy practices (adjusted for basic formal numeracy practices) in the functional MRI sample (total effect, or path *c*; left) and when digit adaptation in the left intraparietal sulcus (IPS) was included in the model (direct effect, or path c'; right). All variables are mean centered, and all analyses were adjusted for parental education and basic formal numeracy practices. Solid lines indicated best-fitting regressions.

home numeracy practices may be related to children's arithmetic fluency and digit adaptation in the IPS (a) because practices impact arithmetic fluency and brain activity (as hypothesized in the model shown in Fig. 1a) or (b) because parents engage in more frequent advanced numeracy practices as they perceive that their child is skilled in mathematics (which may be reflected in both greater arithmetic fluency and enhanced brain sensitivity to numerical information). To disentangle these possibilities, we asked parents to indicate their perception of their child's mathematical skills. As expected, this parental estimate was positively correlated with children's arithmetic fluency, $r(48) = .32$, $p = .012$, 95% CI lower = .09. However, this parental perception was neither correlated with advanced home numeracy practices (after adjustment for parental education and basic formal practices), partial $r(64) = -.01$, $p = .528$, 95% CI lower = −.21, nor with digit adaptation in the IPS (after adjustment for parental education), partial $r(48) = .19$, $p = .099$, 95% CI lower = −.05. When adjusting for this parental estimate of a child's mathematical skill, we found that advanced formal numeracy practices also remained related to children's arithmetic fluency (after adjustment for parental education and basic formal practices), partial $r(48) = .33$, $p = .01$, 95% CI lower = .01 (see Fig. S2a, left, in the Supplemental Material) and digit adaptation in the IPS (after adjustment for parental education and basic formal practices), partial $r(48) = .37$, $p = .004$, 95% CI

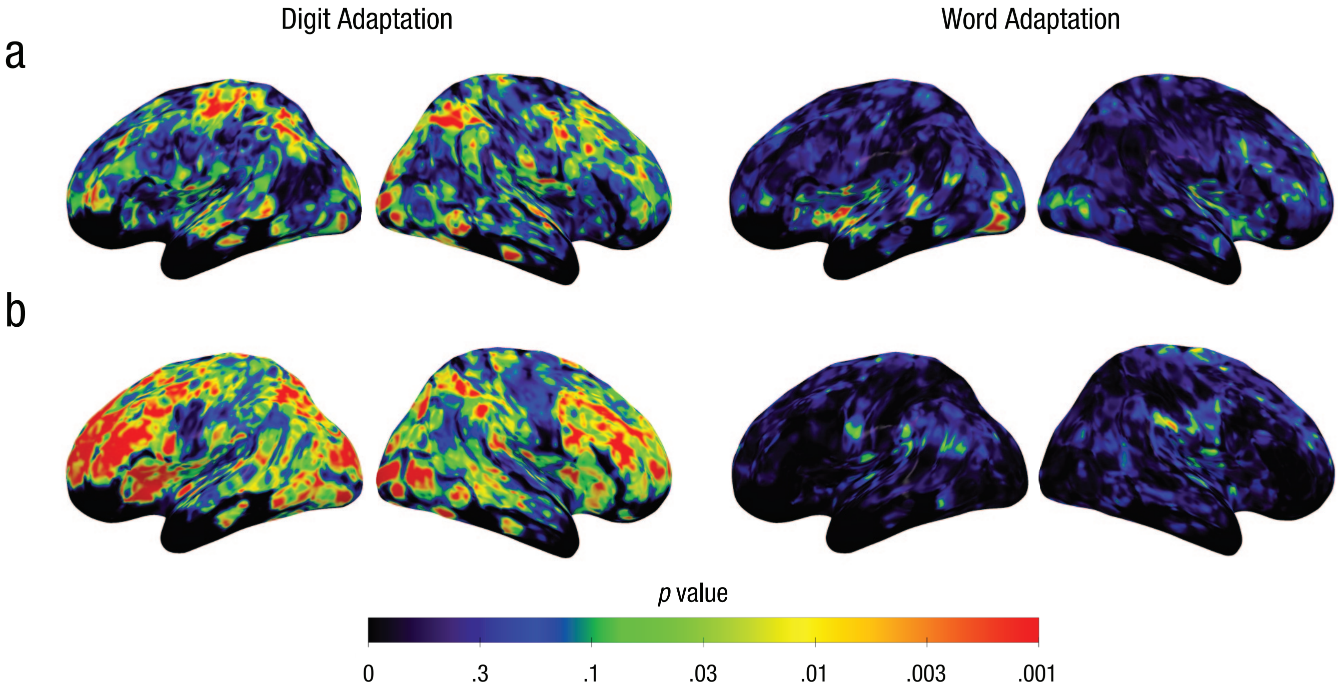

Fig. 6. Unthresholded maps of p values showing the relations between digit and word adaptation, home numeracy practices, and children's arithmetic fluency identified in the mediation-effect parametric-mapping analyses across the whole brain (n = 50 for digit adaptation, n = 44 for word adaptation). In (a), lateral views of the left and right hemispheres show voxels in which neural adaptation to digits (left) and words (right) increased with advanced formal numeracy practices (path a). In (b), lateral views of the left and right hemispheres show voxels in which digit adaptation (left) and word adaptation (right) increased with children's arithmetic fluency (adjusted for advanced formal numeracy practices; path b). All analyses were adjusted for parental education.

lower = .14 (see Fig. S2a, right). Therefore, even though parents were aware of their child's mathematical competence, this awareness did not appear to drive an increase in the frequency of numeracy practices. This is consistent with the causal assumptions of the model in Fig. 1a.

It has also been argued that associations between home practices and children's skills may not uniquely reflect environmental influences but may also stem (at least in part) from genetic predispositions to high academic achievement that parents may pass on to children (these parents are likely to maintain higher quality learning environments than others; Hart et al., 2021). Following a recent proposal by Hart et al. (2021), we attempted to control for this confound by measuring parents' arithmetic fluency as a genetic proxy for predisposition to mathematical achievement. There was no significant positive correlation between parents' and children's arithmetic fluency, $r(64) = .01$, $p = .477$, 95% CI lower = −.23. The relation between advanced formal numeracy practices and children's arithmetic fluency also remained significant when we controlled for parents' arithmetic fluency (after adjustment for parental education and basic formal practices), partial $r(64) = .32$, $p = .004$, 95% CI lower = .12. Overall, then, the association between advanced formal home numeracy practices and children's arithmetic fluency may not be easily explained by the idea that parents have a predisposition to high mathematical achievement.

MEPM results: word adaptation

Because digits were systematically presented at the center of the screen in the digit-adaptation task, it is possible that the relations found above reflect general perceptual-adaptation effects to any kind of symbolic stimuli. To test for this possibility, we ran another MEPM analysis in which we used neural adaptation to words as brain mediator of the relation between advanced formal numeracy practices and children's arithmetic fluency. Indeed, much like in the digit-adaptation task, the word-adaptation task involved symbols (i.e., words) that were repeatedly presented at the center of the screen. Critically, however, these symbols did not carry any numerical information. We did not find any region in which word adaptation was significantly related to numeracy practices (path a) or children's arithmetic fluency (path b; see unthresholded maps of p values in Fig. 6). We also did not find any brain region in which word adaptation affected the relation between numeracy practices and children's arithmetic fluency (path ab). Therefore, the relation between advanced formal numeracy practices and children's arithmetic fluency was specifically explained by symbolic numerical information in the IPS. The whole-brain unthresholded probability maps corresponding to Fig. 5 and Fig. 6 (as well as the IPS mask) are available via NeuroVault at https://identifiers.org/neurovault.collection:9250.

Supplemental analyses

Finally, we performed four sets of supplemental analyses to rule out alternative explanations of our findings. First, the MEPM analyses reported above show that word adaptation did not account for the relation between advanced formal numeracy practices and children's arithmetic fluency. However, this lack of effect might result from a general lack of sensitivity to detect adaptation to words across our sample. To test for this possibility, we examined the significance of word-adaptation effects (i.e., the difference between no-adaptation and adaptation blocks) across all participants (n = 44). Adaptation to words was significant in the left inferior frontal gyrus and left inferior temporal gyrus (Fig. S3a and Table S1), which are regions of the left language-related network that was also found by Perrachione et al. (2016; see Fig. 3b in Perrachione et al., 2016). Thus, Perrachione et al.'s findings regarding overall adaptation to English words were largely replicated using the same task in a different language (i.e., French), demonstrating the reliability of the task.

Second, the MEPM analyses also show that digit adaptation relates to both numeracy practices and arithmetic fluency. However, it remains unclear whether adaptation to digits may be significant in itself in the IPS across participants. Averaging across all participants (n = 50), we found that digit-adaptation effects were significant in a network of frontal and occipital brain regions but not in the IPS (Fig. S3b and Table S1). Because digit adaptation in these regions was neither related to numeracy practices nor arithmetic fluency, these regions might support perceptual or domain-general aspects of digit processing that are not dependent on skills or environmental stimulations. Interestingly, however, overall adaptation to digits was significant (x = 32, y = −94, z = −5), cluster size = 2.3 cc, −log10 (maximum p value) = 5.23, d = 0.62, when we considered the participants with the highest levels of arithmetic fluency (n = 23 after median split of the sample as a function of arithmetic fluency; see Fig. S3c). This was not the case for participants with the lowest levels of fluency (d = −0.36, n = 23). Therefore, the presence of significant adaptation to digits in the IPS might index a relatively high level of arithmetic fluency, which points to a link between automaticity in symbolic number processing in the IPS and symbolic math skills.

Third, as is standard in mediation models, the relation between the mediator (i.e., brain activity) and the outcome (i.e., children's arithmetic fluency) in our MEPM analysis of digit adaptation was controlled for the predictor (i.e., home numeracy practices). However, the same variable cannot be both the outcome and a covariate. Thus, the relation between home numeracy practices and brain activity was not adjusted for children's arithmetic fluency. This raises the question of whether the relation between advanced formal numeracy practices and digit adaptation in the IPS was entirely driven by children's arithmetic fluency. When adjusting for children's arithmetic fluency (as well as for education and basic formal numeracy practices), we found that advanced formal numeracy practices remained positively related to digit adaptation in the left IPS, partial r(48) = .24, p = .043, 95% CI lower = .01 (see Fig. S2a). Therefore, the relation between home numeracy practices and digit adaptation in the IPS does not appear to be uniquely driven by children's arithmetic fluency.

Fourth, because previous studies have shown that symbolic mathematical skills relate more strongly to symbolic than nonsymbolic number processing (De Smedt et al., 2013), the present study focuses on symbolic number processing in the IPS. Nonetheless, nonsymbolic numerical skills have also been related to both mathematical skills (Chen & Li, 2014) and home numeracy practices (Elliott & Bachman, 2018), though evidence for these relations are inconsistent and disputed (De Smedt et al., 2013; Mutaf-Yıldız et al., 2020; Wilkey & Ansari, 2020). To investigate whether the effects shown here would also be obtained using nonsymbolic numerical stimuli, we also presented participants with an exploratory nonsymbolic numerical-adaptation task in which dot arrays were repeatedly presented, either with the same numerosity (adaptation blocks) or with a different numerosity (no-adaptation blocks). Stimuli were controlled for a variety of parameters (see the Supplemental Material and Fig. S4). In contrast to digit adaptation, we did not find any relation between adaptation to numerosities and advanced formal numeracy practices anywhere in the brain. However, numerosity adaptation increased with the frequency of basic formal numeracy practices in a network of frontoparietal regions that included the left IPS (Fig. S4 and Table S1). This suggests that nonsymbolic numerical processing may relate to different aspects of the home numeracy environment than symbolic numerical processing. We also found a significant positive relation between arithmetic fluency and numerosity adaptation in the right (rather than the left) IPS, in keeping with studies demonstrating that symbolic and nonsymbolic numerical processing rely on different neural mechanisms (Wilkey

& Ansari, 2020; Fig. S4 and Table S1). MEPM analyses, however, showed that numerosity adaptation did not explain the relation between either basic or advanced formal practices and arithmetic fluency anywhere in the brain. Thus, only symbolic (not nonsymbolic) number processing appears to account for the relation between numeracy practices and mathematical skills.

Discussion

Here, we set out to explore the relations between home numeracy practices, number-related brain regions, and mathematical skills in 8-year-olds. First, consistent with previous studies (Elliott & Bachman, 2018), our results showed that children's mathematical skills increased with the frequency of home numeracy practices but only if those activities were formal and relatively challenging.

Second, we found an association between children's arithmetic skills and digit-related activity in the IPS, a region that is at the core of human mathematical competence (Nieder, 2016). Such a relation has been suggested in the past (e.g., Bugden et al., 2012). However, previous studies have tended to use active tasks in relatively heterogenous samples (Arsalidou et al., 2018), which can cause differences in brain activity to be confounded by differences in age and task performance (Church et al., 2010). Here, we demonstrated that this relation can be captured using a passive digit-adaptation task in a homogeneous sample of 8-year-olds, thereby measuring how sensitive the IPS is to the passive presentation of symbolic numerical information.

Third, a major novel finding of the present study is that home numeracy practices also relate to digit-related activity in the IPS. This suggests that children benefiting from a higher quality home numeracy environment may have heightened sensitivity to symbolic magnitudes in the IPS. Our results are noteworthy because the only two prior studies that have investigated the relation between the neural bases of mathematical skills and children's home environment (using family SES as a proxy) have found such a relation in language-related regions (Demir-Lira et al., 2015, 2016). Therefore, our study provides the first evidence that disparities in children's home numeracy environments may relate to functional differences in how IPS mechanisms process symbolic magnitudes.

Fourth, we found that the relation between advanced formal numeracy practices and children's arithmetic skills was influenced by the neural response to digits in the left IPS. This is consistent with a model positing that core numerical-processing mechanisms in the IPS mediate the relation between home numeracy environment and children's mathematical skills (Fig. 1a). Critically, the relation between advanced formal numeracy practices and children's arithmetic skills was not influenced by neural adaptation to words, demonstrating that this effect was not explained by a domain-general processing of symbolic information. That relation was also not influenced by neural adaptation to nonsymbolic numerosities, in line with a growing body of studies showing that symbolic number processing is a more consistent predictor of mathematical skills than nonsymbolic processing in children (De Smedt et al., 2013).

Finally, we highlight two main limitations of this work. A first limitation is that our design is cross-sectional and therefore cannot speak to the causal aspects of the model in Figure 1a. That is, although the relations observed are consistent with this model, other models may be compatible with our results. In several of our analyses, we attempted to undermine alternative models. However, the choice of the most plausible mediation model ultimately rests on prior findings, logic, and theoretical considerations (Fiedler et al., 2018). Specifically, the model in Figure 1a is derived from similar research on how the home literacy environment may influence literacy skills. It also rests on the general theoretical framework that disparities in environmental experiences affect brain development, which in turn influences behavioral traits (Farah, 2017). Finally, it should be noted that, although parents filled out our questionnaire at the time of scanning, it also asked parents to reflect on practices that they engaged in in the past. Furthermore, because the home numeracy environment is relatively stable over the years (Tamis-LeMonda et al., 2019), our measure might have captured the quality of the home numeracy environment not only at the time of the study but also when children were younger. Thus, we speculate that there may be temporal precedence of home numeracy practices over IPS activity and mathematical skills measured at age 8. Nonetheless, interventional studies are needed to substantiate this claim, and our findings should be taken as a first critical test for the plausibility of the model shown in Figure 1a.

A second limitation concerns our sample size. To our knowledge, our study involves the largest sample of children completing a passive number-processing task in an MRI scanner (Arsalidou et al., 2018). Our sample was similar to those used in previous studies investigating relations between the home literacy environment and language-related brain regions (Merz et al., 2020; Romeo et al., 2018). Yet recent reports have raised concerns about the replicability of brain–behavior correlations in the sample sizes that are typical in neuroimaging studies (Marek et al., 2020), though replicability depends on experimental considerations (Nee, 2019). Given the complexity of acquiring task-based neuroimaging data in children (Raschle et al., 2012), we believe that an important avenue for addressing replicability concerns in developmental cognitive neuroscience is data sharing. Here, we have made available all individual neuroimaging data, which we hope will encourage meta-analyses, reanalyses, and comparisons with other data sets.

In sum, our findings show that the neural processing of symbolic numerical magnitudes may be affected by experiences beyond the classroom. Our results are consistent with a mechanistic model of how home numeracy practices might affect children's mathematical skills, inspired by similar models of the home literacy environment and children's reading skills (Merz et al., 2020; Romeo et al., 2018). Therefore, our study provides broad support for interventions that are intended to foster the development of the numerical brain by improving home numeracy practices (Gibson et al., 2020).

Transparency

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Author Contributions
C. Girard and J. Prado conceived and designed the study. C. Girard programmed the experiment. C. Girard, T. Bastelica, J. Léone, J. Epinat-Duclos, and L. Longo conducted the experiment. C. Girard analyzed the data under the supervision of J. Prado. C. Girard and J. Prado wrote and revised the manuscript. All authors approved the final manuscript for submission.
Declaration of Conflicting Interests
The author(s) declared that there were no conflicts of interest with respect to the authorship or the publication of this article.
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Open Practices
The task, the electronic version of the questionnaire (in French), and all behavioral data have been made publicly available via Zenodo and can be accessed at http://doi.org/10.5281/zenodo.4965716. The design and analysis plans for the study were not preregistered. This article has received the badges for Open Data and Open Materials. More information about the Open Practices badges can be found at http://www.psychologicalscience.org/publications/badges.

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Supplemental Material

Additional supporting information can be found at http://journals.sagepub.com/doi/suppl/10.1177/09567976211034498

References

Amalric, M., & Dehaene, S. (2016). Origins of the brain networks for advanced mathematics in expert mathematicians. *Proceedings of the National Academy of Sciences, USA*, *113*(18), 4909–4917. https://doi.org/10.1073/pnas.1603205113

Arsalidou, M., Pawliw-Levac, M., Sadeghi, M., & Pascual-Leone, J. (2018). Brain areas associated with numbers and calculations in children: Meta-analyses of fMRI studies. *Developmental Cognitive Neuroscience*, *30*, 239–250. https://doi.org/10.1016/j.dcn.2017.08.002

Bennett, C. M., & Miller, M. B. (2013). fMRI reliability: Influences of task and experimental design. *Cognitive, Affective & Behavioral Neuroscience*, *13*(4), 690–702. https://doi.org/10.3758/s13415-013-0195-1

Bugden, S., Price, G. R., McLean, D. A., & Ansari, D. (2012). The role of the left intraparietal sulcus in the relationship between symbolic number processing and children's arithmetic competence. *Developmental Cognitive Neuroscience*, *2*(4), 448–457. https://doi.org/10.1016/j.dcn.2012.04.001

Chen, Q., & Li, J. (2014). Association between individual differences in non-symbolic number acuity and math performance: A meta-analysis. *Acta Psychologica*, *148*, 163–172. https://doi.org/10.1016/j.actpsy.2014.01.016

Church, J. A., Petersen, S. E., & Schlaggar, B. L. (2010). The "Task B problem" and other considerations in developmental functional neuroimaging. *Human Brain Mapping*, *31*(6), 852–862. https://doi.org/10.1002/hbm.21036

Cognet, G. (2006). *NEMI-2: Nouvelle Echelle Métrique de l'Intelligence-2* [New Metric Scale of Intelligence-2]. Éditions du Centre de Psychologie Appliquée (ECPA).

Cox, R. W., Chen, G., Glen, D. R., Reynolds, R. C., & Taylor, P. A. (2017). fMRI clustering and false-positive rates. *Proceedings of the National Academy of Sciences, USA*, *114*(17), E3370–E3371. https://doi.org/10.1073/pnas.1614961114

Dehaene, S., & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*(2), 384–398. https://doi.org/10.1016/j.neuron.2007.10.004

Demir-Lira, Ö. E., Prado, J., & Booth, J. R. (2015). Parental socioeconomic status and the neural basis of arithmetic: Differential relations to verbal and visuo-spatial representations. *Developmental Science*, *18*(5), 799–814. https://doi.org/10.1111/desc.12268

Demir-Lira, Ö. E., Prado, J., & Booth, J. R. (2016). Neural correlates of math gains vary depending on parental socioeconomic status (SES). *Frontiers in Psychology*, *7*, Article 892. https://doi.org/10.3389/fpsyg.2016.00892

De Smedt, B., Noël, M.-P., Gilmore, C., & Ansari, D. (2013). How do symbolic and non-symbolic numerical magnitude processing skills relate to individual differences in children's mathematical skills? A review of evidence from brain and behavior. *Trends in Neuroscience and Education*, *2*(2), 48–55. https://doi.org/10.1016/j.tine.2013.06.001

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., Pagani, L. S., Feinstein, L., Engel, M., Brooks-Gunn, J., Sexton, H., Duckworth, K., & Japel, C. (2007). School readiness and later achievement. *Developmental Psychology*, *43*(6), 1428–1446. https://doi.org/10.1037/0012-1649.43.6.1428

Dunst, C. J., Hamby, D. W., Wilkie, H., & Dunst, K. S. (2017). Meta-analysis of the relationship between home and family experiences and young children's early numeracy learning. In S. Phillipson, A. Gervasoni, & P. Sullivan (Eds.), *Engaging families as children's first mathematics educators: International perspectives* (pp. 105–125). Springer. https://doi.org/10.1007/978-981-10-2553-2_7

Eickhoff, S. B., Stephan, K. E., Mohlberg, H., Grefkes, C., Fink, G. R., Amunts, K., & Zilles, K. (2005). A new SPM toolbox for combining probabilistic cytoarchitectonic maps and functional imaging data. *NeuroImage*, *25*(4), 1325–1335. https://doi.org/10.1016/j.neuroimage.2004.12.034

Eklund, A., Nichols, T. E., & Knutsson, H. (2016). Cluster failure: Why fMRI inferences for spatial extent have inflated false-positive rates. *Proceedings of the National Academy of Sciences, USA*, *113*(28), 7900–7905. https://doi.org/10.1073/pnas.1602413113

Elliott, L., & Bachman, H. J. (2018). How do parents foster young children's math skills? *Child Development Perspectives*, *12*(1), 16–21. https://doi.org/10.1111/cdep.12249

Farah, M. J. (2017). The neuroscience of socioeconomic status: Correlates, causes, and consequences. *Neuron*, *96*(1), 56–71. https://doi.org/10.1016/j.neuron.2017.08.034

Fiedler, K., Harris, C., & Schott, M. (2018). Unwarranted inferences from statistical mediation tests: An analysis of articles published in 2015. *Journal of Experimental Social Psychology*, *75*, 95–102. https://doi.org/10.1016/j.jesp.2017.11.008

Gibson, D. J., Gunderson, E. A., & Levine, S. C. (2020). Causal effects of parent number talk on preschoolers' number knowledge. *Child Development*, *91*(6), e1162–e1177. https://doi.org/10.1111/cdev.13423

Girard, C., Bastelica, T., Léone, J., Epinat-Duclos, J., Longo, L., & Prado, J. (2021). The relation between home numeracy practices and a variety of math skills in elementary school children. *PLOS ONE*, *16*(9), Article e0255400. https://doi.org/10.1371/journal.pone.0255400

Grill-Spector, K., & Malach, R. (2001). fMR-adaptation: A tool for studying the functional properties of human cortical neurons. *Acta Psychologica*, *107*(1–3), 293–321. https://doi.org/10.1016/s0001-6918(01)00019-1

Hart, S. A., Little, C., & van Bergen, E. (2021). Nurture might be nature: Cautionary tales and proposed solutions. *npj Science of Learning*, *6*(1), Article 2. https://doi.org/10.1038/s41539-020-00079-z

Hayes, A. F. (2018). *Introduction to mediation, moderation, and conditional process analysis: A regression-based approach* (2nd ed.). Guilford Press.

LeFevre, J. A., Skwarchuk, S.-L., Smith-Chant, B., Fast, L., Kamawar, D., & Bisanz, J. (2009). Home numeracy experiences and children's math performance in the early school years. *Canadian Journal of Behavioural Science*, *41*, 55–66. https://doi.org/10.1037/a0014532

Luna, B., Velanova, K., & Geier, C. F. (2010). Methodological approaches in developmental neuroimaging studies. *Human Brain Mapping*, *31*(6), 863–871. https://doi.org/10.1002/hbm.21073

Marek, S., Tervo-Clemmens, B., Calabro, F. J., Montez, D. F., Kay, B. P., Hatoum, A. S., Donohue, M. R., Foran, W., Miller, R. L., Feczko, E., Miranda-Dominguez, O., Graham, A. M., Earl, E. A., Perrone, A. J., Cordova, M., Doyle, O., Moore, L. A., Conan, G., Uriarte, J., . . . Dosenbach, N. U. F. (2020). *Towards reproducible brain-wide association studies*. BioRxiv. https://doi.org/10.1101/2020.08.21.257758

Mazaika, P. K., Hoeft, F., Glover, G. H., & Reiss, A. L. (2009). Methods and software for fMRI analysis for clinical subjects. *NeuroImage*, *47* (Supp. 1), S58. https://doi.org/10.1016/S1053-8119(09)70238-1

Merz, E. C., Maskus, E. A., Melvin, S. A., He, X., & Noble, K. G. (2020). Socioeconomic disparities in language input are associated with children's language-related brain structure and reading skills. *Child Development*, *91*(3), 846–860. https://doi.org/10.1111/cdev.13239

Merz, E. C., Wiltshire, C. A., & Noble, K. G. (2019). Socioeconomic inequality and the developing brain: Spotlight on language and executive function. *Child Development Perspectives*, *13*(1), 15–20. https://doi.org/10.1111/cdep.12305

Mutaf-Yıldız, B., Sasanguie, D., De Smedt, B., & Reynvoet, B. (2020). Probing the relationship between home numeracy and children's mathematical skills: A systematic review. *Frontiers in Psychology*, *11*, Article 2074. https://doi.org/10.3389/fpsyg.2020.02074

Nee, D. E. (2019). fMRI replicability depends upon sufficient individual-level data. *Communications Biology*, *2*, Article 130. https://doi.org/10.1038/s42003-019-0378-6

Nieder, A. (2016). The neuronal code for number. *Nature Reviews Neuroscience*, *17*(6), 366–382. https://doi.org/10.1038/nrn.2016.40

Pallier, C., & New, B. (2019). OpenLexicon. *GitHub*. https://github.com/chrplr/openlexicon

Peirce, J., Gray, J. R., Simpson, S., MacAskill, M., Höchenberger, R., Sogo, H., Kastman, E., & Lindeløv, J. K. (2019). PsychoPy2: Experiments in behavior made easy. *Behavior Research Methods*, *51*(1), 195–203. https://doi.org/10.3758/s13428-018-01193-y

Perrachione, T. K., Del Tufo, S. N., Winter, R., Murtagh, J., Cyr, A., Chang, P., Halverson, K., Ghosh, S. S., Christodoulou, J. A., & Gabrieli, J. D. E. (2016). Dysfunction of rapid neural adaptation in dyslexia. *Neuron*, *92*(6), 1383–1397. https://doi.org/10.1016/j.neuron.2016.11.020

Price, G. R., Mazzocco, M. M. M., & Ansari, D. (2013). Why mental arithmetic counts: Brain activation during single digit arithmetic predicts high school math scores. *The Journal of Neuroscience*, *33*(1), 156–163. https://doi.org/10.1523/JNEUROSCI.2936-12.2013

Raschle, N., Zuk, J., Ortiz-Mantilla, S., Sliva, D. D., Franceschi, A., Grant, P. E., Benasich, A. A., & Gaab, N. (2012). Pediatric neuroimaging in early childhood and infancy: Challenges and practical guidelines. *Annals of the New York Academy of Sciences*, *1252*, 43–50. https://doi.org/10.1111/j.1749-6632.2012.06457.x

Robin, M. (2019). More people live in a median household in the western regions. In *Insee Focus* (No. 148). Institut National de la Statistique et des Études Économiques.

Romeo, R. R., Leonard, J. A., Robinson, S. T., West, M. R., Mackey, A. P., Rowe, M. L., & Gabrieli, J. D. E. (2018). Beyond the 30-million-word gap: Children's conversational exposure is associated with language-related brain function. *Psychological Science*, *29*(5), 700–710. https://doi.org/10.1177/0956797617742725

Schwartz, F., Epinat-Duclos, J., Léone, J., Poisson, A., & Prado, J. (2018). Impaired neural processing of transitive relations in children with math learning difficulty. *NeuroImage: Clinical*, *20*, 1255–1265. https://doi.org/10.1016/j.nicl.2018.10.020

Shrout, P. E., & Bolger, N. (2002). Mediation in experimental and nonexperimental studies: New procedures and recommendations. *Psychological Methods*, *7*(4), 422–445. https://doi.org/10.1037/1082-989X.7.4.422

Sokolowski, H. M., & Ansari, D. (2018). Understanding the effects of education through the lens of biology. *npj Science of Learning*, *3*, Article 17. https://doi.org/10.1038/s41539-018-0032-y

Tamis-LeMonda, C. S., Luo, R., McFadden, K. E., Bandel, E. T., & Vallotton, C. (2019). Early home learning environment predicts children's 5th grade academic skills. *Applied Developmental Science*, *23*(2), 153–169. https://doi.org/10.1080/10888691.2017.1345634

Wager, T. D., Davidson, M. L., Hughes, B. L., Lindquist, M. A., & Ochsner, K. N. (2008). Prefrontal-subcortical pathways mediating successful emotion regulation. *Neuron*, *59*(6), 1037–1050. https://doi.org/10.1016/j.neuron.2008.09.006

Wilkey, E. D., & Ansari, D. (2020). Challenging the neurobiological link between number sense and symbolic numerical abilities. *Annals of the New York Academy of Sciences*, *1464*(1), 76–98. https://doi.org/10.1111/nyas.14225

Woodcock, T. A., McGrew, K. S., & Mather, N. (2001). *Woodcock-Johnson III Tests of Achievement*. Riverside Publishing.

Zamarian, L., Ischebeck, A., & Delazer, M. (2009). Neuroscience of learning arithmetic—Evidence from brain imaging studies. *Neuroscience and Biobehavioral Reviews*, *33*(6), 909–925. https://doi.org/10.1016/j.neubiorev.2009.03.005